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Initial Identification and Investigation of Parameters for Choosing the Most Appropriate Rapidly Assembled or Deployable Structure

by

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Initial Identification and Investigation of Parameters for Choosing the Most Appropriate Rapidly Assembled or Deployable Structure

Approved by
Supervising Committee:

Dedication

I dedicate this thesis to my wife, Barrie, who provided much love and support during this past year.

Acknowledgements

I take this opportunity to thank Dr. Katherine Liapi for her guidance and encouragement, as well as for allowing me to pursue topics and ideas that interested me. I also thank my father who provided an outside expert opinion and proofread this work.

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CHAPTER ONE

INTRODUCTION

It is well known that a young engineer in the professional arena is commonly faced with problems that are unlike what he has learned to solve through the rigors of his academic education. In particular, the amount of known information is small compared to what is uncertain; it may be difficult to see the real problem because it is hard to place the situation in the proper context. Unlike in formal engineering education, the problem may not have a correct answer. Instead a matrix of options may need to be generated and the decision may need to be based on financial analysis and political correctness along with technical merit. A complete factual analysis that will lead to more than one option may help in such decision-making.

The necessity to base decisions on more than the issues typically addressed in engineering design classes may indicate that a decision among technically acceptable alternatives is driven by specific financial, personal, or other needs of the user. From trouble shooting computer chip circuits to performing structural analysis on concrete beams to designing a new house, an interdisciplinary approach involving a plethora of issues must be used in our dynamic culture.

Focusing now on engineering practices that deal with building structures, it is well accepted that a technically sound structure needs to serve a basic function and fulfill a fundamental need together with a great number of secondary needs. There can be different ways that the structure addresses this need or, just as important, additional needs that structure may also have to satisfy. For example, shelter is a basic human need that must be met. For many years the cave fulfilled this primordial human need for protection from the climate. But that shelter is useless unless it meets other functional or safety requirements such as accessibility and protection from fire. As society advanced, the effort to address more complex or different psychological and physiological human needs at the same time gave origin to several interpretations and expressions of structures while still meeting the basic need for protection. Thatched huts, wooden cabins, and castles were built in increasing complexity to, among other things, showcase wealth and warehouse food.

One can define and recognize structures that serve different basic needs. Certainly the structures in which someone lives and works easily come to mind. Other types of familiar structures that primarily serve educational, religious, and recreational needs can be readily identified. A special type of structures that share a common mission, but at the same time must address several other needs, includes temporary facilities, or facilities that need to be erected for a short time, such as temporary warehouse space for a business or a pavilion used for the 2002 Winter Olympic games in Salt Lake City, Utah. Fabric structures used to house

refugees from a south Pacific typhoon or homeless families from military conflicts are also representative examples of temporary structure needs. A structure might also be required in an area that is environmentally sensitive or not easily accessible by humans. The structure may be required immediately, there may be time to plan completely the approach, or reality may lie somewhere in between. Maybe the structure needs to be built from the ground up, or maybe it can be bought in the form of a pre-engineered kit ready to be assembled on site.

A rapidly assembled structure can be built on site more quickly (due to pre-assembly or specific mechanical connections) than another structure built from its component parts. A deployable structure is one that can be pre-assembled, relocated to a site, erected and used, then disassembled and moved to another site. The advantages offered by such structures are significant when speed of transportation and erection are important requirements (Gantes 1991). Rapidly assembled or deployable (RAD) structures have been used for centuries and continue to be used today. Nomadic tribes crossing the deserts of Africa and American Indians roaming the plains of North America carried their living quarters with them as they traveled. Military forces of many nations mobilize with tents, weapon systems, equipment, and bridges that are mobile and able to be erected and disassembled expeditiously. Weekend campers at the local park and backpackers ascending tall mountains rely on fabric tents for warmth and protection.

When an engineer is given a problem in which he is tasked with proposing a structure to meet specific needs, more often than not he will be given a broad assignment and he must determine exactly all the needs, primary and secondary, and then develop a constructible solution meeting those needs or parameters. The priority of the needs shifts to address speed and mobility when the structure must be built quickly (in response to a natural disaster) or in a remote location. Without a clear vision of the great number of options available or the many variables involved, the problem is daunting. A framework is needed around which the approach is made using a rapidly assembled or deployable (RAD) structure.

After reviewing research findings that address various aspects of RAD structures, it was realized that a void existed when trying to find the right structure for a given set of conditions. It became obvious immediately that some type of selection criteria should be developed to aid an engineer in analyzing the complete situation, condensing the information into the key nuggets, and efficiently choosing the most appropriate solution using these parameters.

Based upon the information collected, parameters can be created and categorized. In an attempt to present some order to a rather large and unwieldy situation, the parameters are analyzed to ensure they are specific enough to shape the thought process while being general enough to allow creativity and understanding to occur.

1.1 OBJECTIVES

The main objective of this thesis is to develop and categorize parameters for choosing the most appropriate rapidly assembled or deployable structure. Other objectives include: to provide an overview of the existing classifications of deployable and moveable structures, to propose a logical measurement or metric for each parameter that is developed, and to demonstrate through a plausible case study the usefulness of the parameters in selecting a structure identified by current researchers.

1.2 THESIS LAYOUT

Chapter One introduces the topic of rapidly assembled or deployable structures and identifies the need for the development of a methodology for addressing selection criteria in a comprehensive and coherent manner. It also sets the context in which these types of structures may be appropriate and confirms the relevance of this work.

Chapter Two of this thesis presents planning and design processes, applicable to conventional structures, which can also be helpful in the selection process and or design of RAD structures. A systems approach is presented to confirm that a thorough analysis of the natural and built context needs to be conducted when a RAD structure is considered.

Chapter Three presents the research to date in this field, and shows that the main researchers classify these structures based upon their features and properties. This thesis chooses the opposite viewpoint and gathers data about a need to fill and then searches for a structure that satisfies the need.

Chapter Four presents the parameters that were developed and classified into four general categories: function and use, contextual response, material properties and methods, and financial. Metrics are introduced to measure each parameter and explain the rationale behind its selection. Examples are offered to enhance the reader's understanding.

Chapter Five presents a scenario, which showcases the usefulness of the proposed approach to the selection process. In developing a case study, a realistic scenario was chosen to emphasize the practicality of the issues in response to plausible situations.

Chapter Six concludes the paper and suggests areas for follow-on effort.

CHAPTER TWO

PLANNING METHODOLOGY FOR RAD STRUCTURES

Several methodologies exist for planning and designing permanent structures. A thorough understanding of the intended use of the structure and the functions that will be performed in or around the structure are critical factors in providing the larger picture that will determine critical decisions about its planning, design and construction. The built or natural context of a structure is a major determinant factor in making decisions about its design and construction. In addition, the reasons behind and the logic driving the factors that are to be taken into account in the decision making process regarding the design or choice of a structure should be well understood in order to meet the project's goals. For example, an office space with full height walls between cubicles offers privacy to its workers but discourages face-to-face communication; this works well where financial information is discussed, but may not satisfy a manager's intention of promoting openness and interaction among the staff. A decision to only provide central cooling systems without natural ventilation for a mechanic's shop shows that in the planning stage of the project the issue that fresh air is of primary importance for such a function was not given the proper attention.

From a different point of view, it is accepted in the construction industry that more thorough planning results in a better project having less schedule delays and cost growth, and better meeting the user's needs. Effective planning means

making important decisions early and using the results to guide the remainder of the process.

2.1 DECISION-MAKING PROCESS

Decision-making typically means making a choice in the present moment. What can easily be forgotten is the process leading up to that final moment when a direction is chosen and a commitment is made. The majority of effort in the decision-making process is expended in reaching the point where an educated individual is able to make a rational selection among choices. "Decision making comprises three principal phases: *finding occasions for making a decision*; *finding possible courses of action*; and *choosing among courses of action* (Simon 1960). Simon classifies the decision-making process into three phases, *Intelligence, Design*, and *Choice.* As shown in Figure 2.1, a fourth phase, *Implementation,* is added.

The *Intelligence* phase is characterized by searching for the information and conditions prerequisite for the decision. It means understanding the context in which the decision is to be made along with the perspective of the decision maker. This can explain biases toward a particular option. Defining the parameters for the selection of RAD structures, introduced later in this paper, is a part of the Intelligence phase in project planning; the user is given the tools with which the scenario can be dissected and a comprehensive understanding of the needs can be gained.

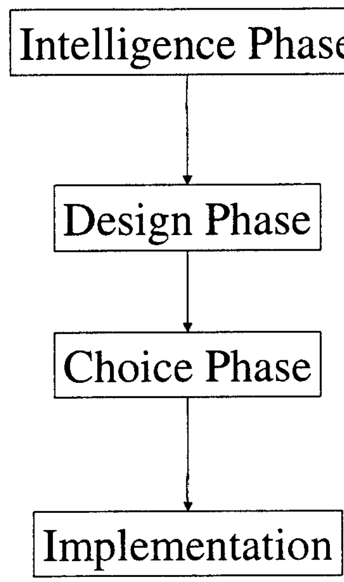

Figure 2.1 Adapted from Simon's Decision-Making Process

Exploring options and fully understanding their implications encompasses the *Design* phase. The possible alternatives must be considered and their outcomes understood so the decision-maker can act upon fact and analysis and not conjecture or opinion. The individuals involved in making the decision must develop realistic courses of action that consider relevant issues and weigh risks associated with them. Various ways of addressing the conditions discovered during the Intelligence phase must be examined.

The *Choice* phase is summarized by the selection of a specific option from among those developed during the Design phase. In exploring the various options, the decision-maker must bring experience to bear when making the choice. A decision so obvious as not to require the judgment of the decision-maker is not as much of a decision as it is the next step in a pre-programmed sequence. The ability to take into account the nuances and subtleties of the issue at hand can make the chosen path the better one of the given alternatives.

An *Implementation* phase is necessary to turn a decision into reality. Once a decision is reached, it must be acted upon and brought to life. The next step has been chosen, so that what remains to be done is simply to proceed in the given direction. The ability to understand the context of the project, create various options, select the one best meeting the project's goals, and implement the solution is desired.

The logic in choosing a RAD structure is not fundamentally different from determining a traditional structure. The tailoring process of producing a RAD structure can easily occur within the logical guidelines presented.

2.2 A SIX-STEP ARCHITECTURAL PLANNING / DESIGN PROCESS

If the context is limited from decision-making in general to designing a space for a user, the perspective changes. Consideration of the physical space and its properties and how those must be adapted to accommodate the client's

objectives become paramount as decisions are explored and made. Kilmer and Kilmer propose a six-step programming process for the design of interior spaces: *establish the goals, gather and analyze facts, specify needs, evaluate, organize and decide, and present conclusions* (Kilmer and Kilmer 1992). Since a RAD structure is basically creating an interior space, this model is applicable. Figure 2.2 shows the process.

Establish Goals

Gather and Analyze Facts

Specify Needs

Evaluate

Organize and Decide

Present Conclusions

Figure 2.2 The Programming Process

Establishing the goals begins the process. Typically, asking the following four relevant questions and prioritizing the answers performs the goal setting:

- What is to be achieved?
- Why is it to be achieved?
- What are the client goals?
- What are the design goals (Kilmer and Kilmer 1992)?

This appears simple, but the difficulty lies in satisfying multiple goals simultaneously, particularly when the goals seem exclusive of each other. As in the earlier decision-making process, the context in which the space will be created needs to be seriously considered. Many ways may exist to meet the user's needs. (User needs will be addressed in a later section). The broader implications of the project need to be well understood so the most appropriate solution meshes the overall goals along with the user needs.

Fact gathering and analysis comes next. Pertinent facts must be collected and matched with the expectations of the user. A client may have a particular approach in mind; this may or may not be justified by the existing realities of the situation. Data must be organized to find the kernels of information critical to the project's success. Applicable federal, state, and local code requirements must be known and met. A thorough understanding and analysis of the user's needs results in a better functioning space. Site-specific information, technology available in the area, level of expertise in relation to the workforce, and other possible resources need to be known. Information about the infrastructure is also critical and must be collected at this level. Other information like the community's response and predisposition to previous undertakings may also be gauged and taken into account. Likewise, a structure should be designed with the long-term goals of the project and the needs of the user in mind. An example would be planning the structures for a tourist facility on a remote island. All of

the above issues must be considered, including, as a simple example, whether it makes sense to use aluminum windows, if the workforce is capable of installing them, and how the windows can be transported there.

On a scale that is smaller than the goals of the project, the *needs* of the client and the user must be known and understood. The needs of the problem, such as space requirements and available funds, are also important considerations. Understanding the physiological and psychological needs of the user is obviously part of the analytic phase. A facility may be constructed that has aesthetic value without satisfying the user's needs on a full-time basis. A special situation arises when the structure is needed in a relatively remote location that restricts full access to machinery and equipment necessary to stage and assemble the components. A solution may be found meeting both the requirements and restrictions, or a compromise may be made so that a different type of structure is erected in a nearby location having better accessibility. Independent of the path to the solution, understanding the end use of the facility directly contributes to the best solution.

The fourth step in creating an interior space involves *evaluating the goals, facts, and needs*. The value of each goal and need is related to the facts of the project. Alternatives should be considered and deemed worthy of additional investigation if they appear as realistic and appropriate solutions. The various

approaches may be ranked using numerical criteria; this helps balance the normal subjectivity present in making a choice.

Organizing and deciding upon an optimum solution is the next step. After evaluating the issues at hand, the optimum decision is made. Akin to the *Choice phase* of Simon's decision-making process, experience is key when making the commitments to meet the user's goals and needs within the existing conditions. Conclusions are drawn about the best choice from among possible options, possibly made obvious when viewed in the organized format.

"The last step of the programming process is to *present or communicate the findings* to the client and other parties involved in the situation (Kilmer and Kilmer 1992)." Presenting the conclusions should confirm that the specific needs and broad goals were met. The conclusions should also show how existing conditions of the project, whether they are climatic, budgetary, time-related, or very specific in nature, are satisfied by the chosen option. The user should be comfortable that the issues he raised, along with the unknowns discovered by the engineer, are adequately addressed. For example, a client might need an addition to an existing facility. The client may fully expect that a traditional structure, with full foundation, walls, and roofing system must be built. After consulting with a savvy professional that understands the context of the facility, is familiar with applicable regulations, and has worked diligently to determine exactly what the client needs, the designer may propose a retractable structure with accordion

walls as the solution. This may cost more, but it provides the user with flexibility and draws extra (and desired) attention to an otherwise plain building

Planning and decision-making are important stages in the development of any structure. Understanding basic decision-making skills and using a simple methodology are necessary in choosing the most appropriate RAD structure.

2.3 CRITERIA FOR RAD STRUCTURES

In the discussion of programming and decision-making, examples were given of various parameters critical for a facility. The function, size, location, and cost of a structure are critical issues for traditional structures as well as rapidly assembled and deployable ones. For RAD structures, additional project requirements arise. Mobility of the structure may be absolutely essential, as in the case of a facility used by circus performers in numerous cities throughout the year. A structure that has to last for only a short duration, like a temporary roof over a storm damaged building, is seen differently than the replacement roof for the building. Speed is crucial when people need shelter due to a devastating earthquake.

The important point, shown by Figure 2.3, is that parameters like mobility, transience (temporary in nature), and construction speed may override traditional and well-known issues like function and cost when consideration is given to using a RAD structure. A user may be willing to pay a premium price to have the

facility available for immediate use, which just may be impossible using a traditional facility. The client may take more risk from snow loading to have a structure that is easily disassembled and stored during non-peak business days. Again, the importance is in knowing that these key requirements of speed, mobility, and transience are more critical than others. By finding a way to capture and understand these issues, the needs and requirements of the project can be more appropriately addressed.

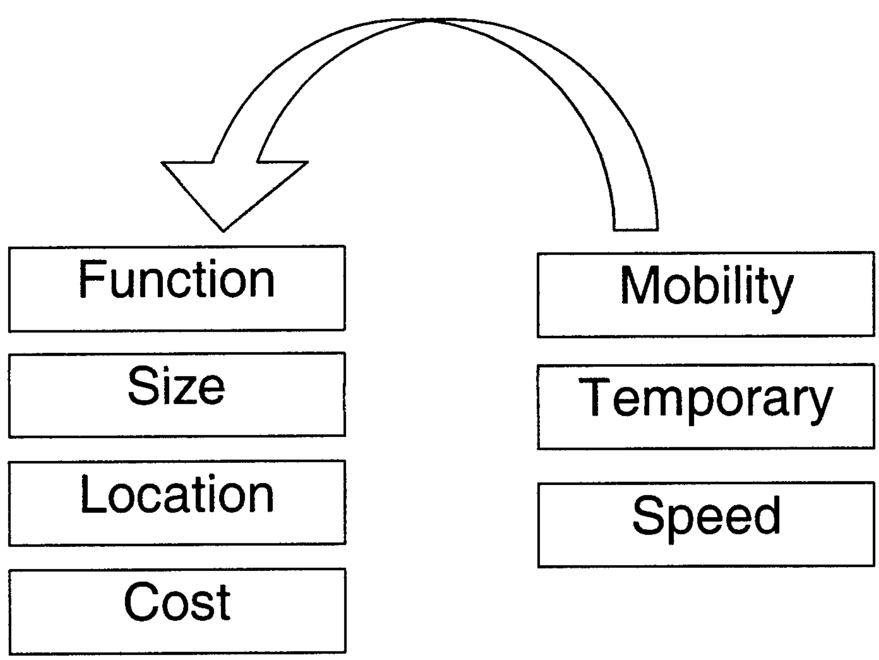

Figure 2.3 Hierarchy of Traditional Structure vs. RAD Structure

CHAPTER THREE

CLASSIFICATIONS OF RAD STRUCTURES

Since they provide viable alternatives to conventional structures, rapidly assembled or deployable structures are currently under investigation in several research centers such as the Massachusetts Institute of Technology, the Laboratoire de Mécanique et Génie Civil, Université Montpellier II in France, and the University of Coruña in Spain. Various issues in their design have been addressed by S. Pellegrino in the Department of Engineering at the University of Cambridge and in a series of conferences organized by F. Escrig of the School of Architecture at the University of Seville in Spain and C.A. Brebbia of the Wessex Institute of Technology in Great Britain. The first conference, entitled Mobile And Rapidly Assembled Structures (MARAS) took place in Southampton, Great Britain in 1991. This has been followed by two other international conferences in 1996 (Seville) and 2000 (Australia). Another researcher, T. Robbin recommends that these structures are the most appropriate for several cases of permanent solutions too because of some special features they present (Robbin 1996). Being temporary in nature, a RAD structure does not have to be the permanent solution to an issue; it can be the best solution meeting today's needs.

A universally accepted method or approach for classifying rapidly assembled or deployable structures does not exist. After listing the uses and

benefits of RAD structures, this chapter presents and compares some current methods for delineating RAD structures into meaningful groupings.

3.1 USES AND BENEFITS OF RAD STRUCTURES

The uses for a RAD structure are wide and varied. These structures can be used in wartime and contingency operations to provide shelter and support such as berthing tents, hospitals, administration, food preparation, distribution and storage of goods, equipment assembly, and maintenance areas. They can be used during disaster recovery and relief operations, providing headquarters for U.N. personnel and life saving supplies for refugees and victims. A RAD structure might be the right answer at a county fair or Olympic venue due to the temporary need of the structure and the desire to minimize impact to the environment.

RAD structures bring tangible benefits to the users due to some unique characteristics. The speed of construction and ease of disassembly allow for the removal of a particular RAD structure and possible use of another one, or of the reconfiguration of components to meet the new need. The replaced structure is not discarded but placed in storage for future use. In today's environmentally conscious world, minimizing environmental impact by using less material to create a temporary and moveable structure is factored heavily into pre-project planning. If transportability to a remote or inaccessible site is a key in solving the need for a structure, a RAD structure may be the right answer. The shortened erection time and adaptability of these structures mandates their use in many

situations. When needed, these qualities make their use practical and worth considering.

3.2 BULSON'S CLASSIFICATION OF RAPIDLY ASSEMBLED STRUCTURES

Structures have historically been classified into groups; the most widely used method is to categorize structures by their use, form, and material. The use of a structure explains why it was created and how it will function. This is shown in the difference between a bridge and building. The structural form, whether thin-walled or a shell, exemplifies how it is made and how it supports its own weight and the weight due to its intended use. Steel, concrete, and aluminum are examples of materials that are typically encountered in traditional structures. Although this basic way of separation works well for traditional structures, it is not appropriate when considering rapidly assembled ones (Bulson 1991). The diversity of the field leads Bulson to classify rapidly assembled structures into the following areas based upon their anatomy and way by which parts of the structures are attached to each other:

- Hinged
- Pinned
- Clamped
- Sliding
- Fabric

Bulson defines a *hinged* structure as one in which pins or joints that allow for articulation but permanently join the elements. Linkages or sliding connections stabilize the structure in the open position. The lounge chair is a simple example where manual effort is used for unfolding; the undercarriage of an aircraft is a much more complex one involving hydraulics to perform the motion. The design of the joint is critical in this hinged category, since overall joints represent 20%-30% of the weight of the structure, and weight is a key parameter.

One significant disadvantage of hinged structures is that the stowed weight of the unit equals the deployed weight. The entire structure must be supported after assembly has occurred as well as during the articulation process. This limits the size of the structure if individuals without appropriate equipment are to move and display it. Even if machines are used, a mobile support system may be required, and this also limits the range of deployment.

Pinned structures are those in which the elements are transported separately and assembled on site using pins or bolts. Bulson states that bolting may be too slow, so inserting pins into jaws or shaped heads into slots are the preferred methods. Military bridges using structural panels are well known examples in this category. Pinned structures can take on numerous configurations using the same pieces, which are often interchangeable. Assembly on site allows for transportation of the components separately. This increases the flexibility of

the assembly process and minimizes the use of equipment required to handle pieces.

In a framework type of pinned structure, the weight of the joints is greater than if the same structure were built without requiring rapid assembly. Conservatively speaking, Bulson estimates that the weight increases by 10% when taking a basic welded structure and making it capable of being rapidly assembled. This 10% is the result of using larger components to handle the localized stresses at the joints. The stress is greater since groups of bolts are replaced with one larger pin or bolt that is more quickly assembled, along with larger lugs and jaws on the component ends. The joints, critical to the structural integrity and behavior of the structures because they determine the direction of motion and degrees of freedom, "need to withstand the stresses created during the motion of the structure, minimize the friction between the parts, and avoid fatigue of the materials (Liapi 2001)."

In a *clamped* structure, members are single bars or tubes connected by clamping elements to form loose frames. Scaffolding is a common application of this principle. Similar to pinned structures, the components can be transported separately making for easier shipment and handling. The elements are interchangeable, so a missing or damaged part can be easily replaced.

Clamped structures have two main disadvantages according to Bulson. First, the size and weight of the clamps can hinder the structure's use. Also, unless components are clamped in the fully extended position, there is a length of unused member (outside the clamp) that unnecessarily adds to the weight of the structure and may protrude and interfere with another section of the structure or the user.

Sliding structures have elements that deploy from a stowed configuration by sliding. The pins, bolts or clamps of the previously discussed categories are replaced by telescoping hydraulic or pneumatic components. A telescoping gangway leading from the airport walkway to an airplane is a good example.

The fundamental drawback when using sliding structures is the overlap among sliding members; butt welds will not suffice. In components where bending and shear are taken into primary consideration, the overlap must be considerable to counteract local stresses in the overlapped area. If the telescopic columns are used in compression, the amount of overlap is an important parameter when analyzing the stability of the structure. Like hinged structures, sliding structures weigh the same whether stowed or deployed. This may limit transportation and deployment options.

The last category of rapidly assembled structures according to Bulson is *fabric*, defined by the dismantling of flexible, foldable materials for ease of

stowage and transportation. Pressure (often air) is introduced to achieve structural integrity of items like parachutes and balloon structures. The greatest benefit from using a fabric structure is the low ratio of stored volume to deployed volume; a packed tent occupies just a few percent of its erected volume.

Four of the previous categories (hinged, pinned, clamped, and sliding) of rapidly assembled structures have similar limitations; fabric structures have different drawbacks. Fabric structures react severely to localized loads and are easily damaged by objects that would not affect the components of other structures. They may rely on a compressor to maintain integrity, and generally have a short life span, both in storage and when deployed.

Bulson gives some consideration to overall drawbacks of using rapidly assembled structures. As described with hinged structures, the weight of the joint is substantial, accounting for 20% to 30% of the total structural weight. The life of the joint may be less than the life of the components it joins, due to the disturbance of the material of the components. When analyzing the deployed condition of the structure against its stowed condition, the weight of the components and their main dimensions, the cost of labor to deploy the structure, and equipment needed for unpacking and deployment is likely to be significant. The life cycle cost of a rapidly assembled structure may be greater than a conventional structure performing the same function. Complex joints, expensive

materials, vulnerability to damage, cost of deployment and storage, and transportation fees drive the overall cost of a rapidly assembled structure upward.

3.3 ESCRIG'S CLASSIFICATION OF DEPLOYABLE STRUCTURES

Escrig, a leading researcher in the field, describes distinct types of deployable structures without clearly providing the basis for his classification. It appears that his taxonomy is based on a combination of material, shape and method of deployment. He classifies deployable structures into eight categories:

- Tensile folding
- Tensegrity roofs
- Retractable roofs
- Foldable
- Umbrella
- Mobile
- Lifting
- Deployable (Escrig 1996).

Tensile folding structures rely on the tension of the structural components to support the structure and give it shape. When not deployed, this type of structure can be folded into a much smaller volume than when it is deployed. Figure 3.1 is a good example of what Taillibert produced for a swimming pool cover in Paris (Escrig 1996).

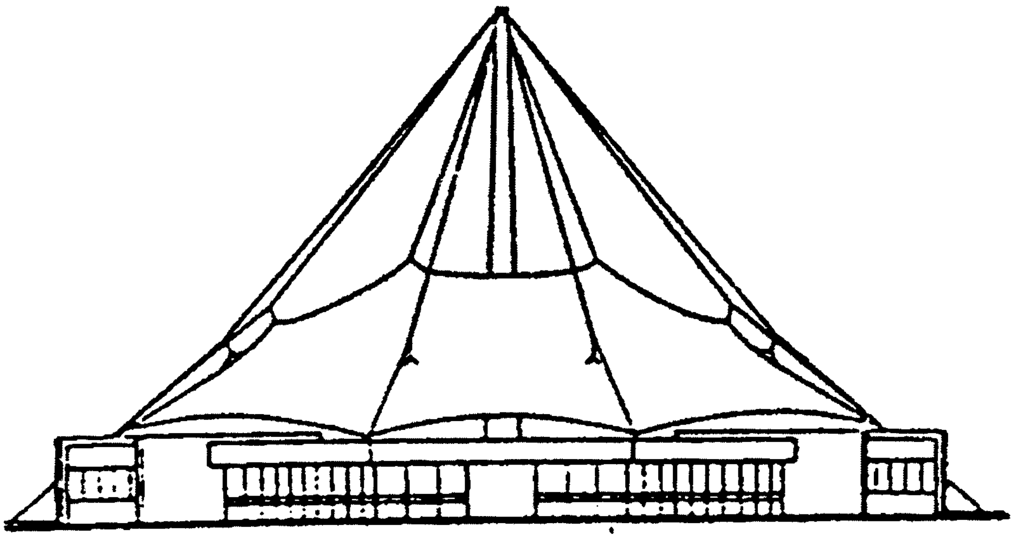

Figure 3.1 Swimming Pool Cover from Escrig 1996

Tensegrity roofs are a specific application of tensile structures. Tensegrity structures are self-supported, internally pre-stressed structures with discontinued compression: parts under compression are not in direct contact with one another and are held together by intermediate pre-stressed members. They are inherently collapsible and deployable in the non pre-stressed state. This specific feature saves erection time and money and is what suggests their potential application in building construction as retractable or deployable structures.

Figure 3.2 is a typical example of a tensegrity roof, which was used by Geiger in his design of the Suncoast Dome. Unlike a tensile folding structure, the roof cannot change its form. Its key characteristic of being lightweight allows it

to be easily installed and dismantled, which results in a shortened construction time, reduced cost, and minimized expense of the work force to dangerous roofing work.

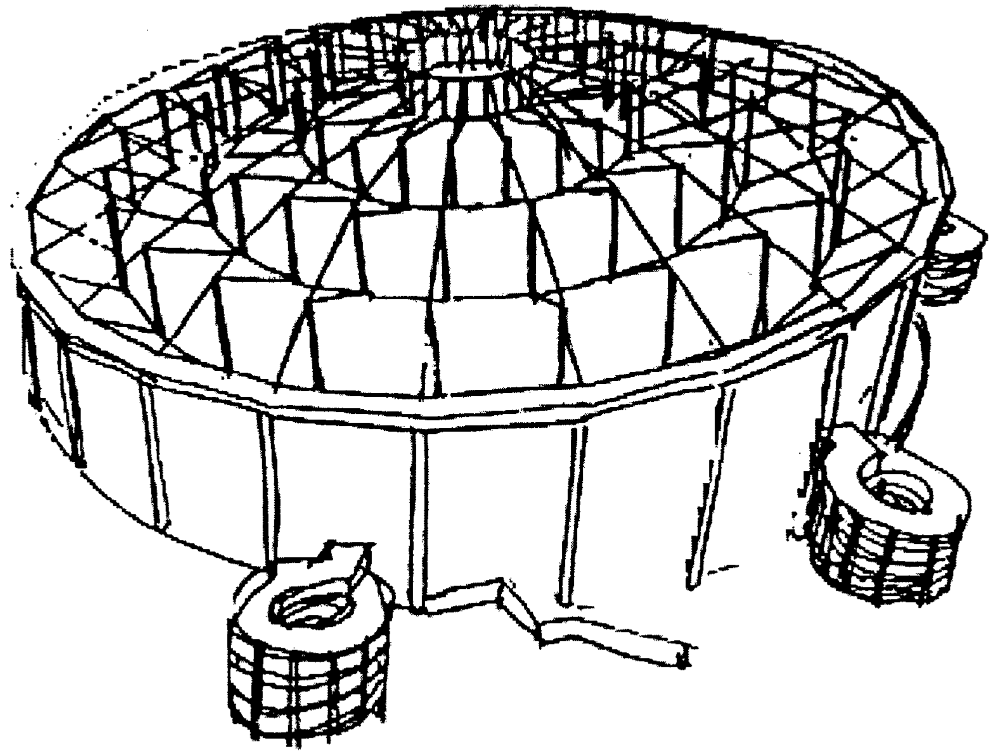

Figure 3.2 Suncoast Dome from Escrig 1996

Retractable roofs are the third type of deployable structures according to Escrig's classification. Kazuo Ishii, a world-renowned expert on the design and construction of retractable roofs, says: "A retractable roof structure is the type of structure in which part of, or all of the entire roof can be moved or retracted within a short period of time so that the building can be used with the roof both in

an open state or a closed state (Ishii 2000)." Used during the time of the Roman Empire, retractable roofs again became a viable option for roof design after the 1930's due to the advancements in crane technology at the same time. Figure 3.3 shows examples of such roofing systems.

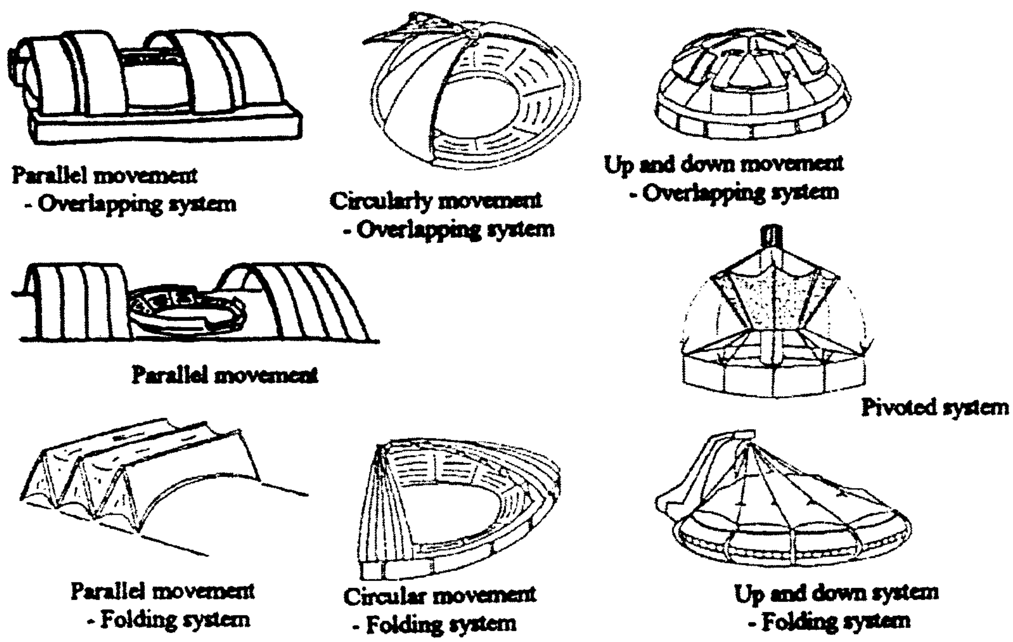

Figure 3.3 Roofing Systems from Structural Design of Retractable Roof Structures

Ishii groups retractable roofs into two categories:

- Roofs in which a frame structure is used in roof parts, and materials such as glass, plastics, membrane materials and metal plates are stretched over the frame structure

- Roofs that are opened and closed by folding the membrane materials of which they are made (Ishii 2000)

A membrane or fabric that is *foldable* is another type of structure. What distinguishes this type from being included in the retractable roof category is that the structural components are "hinged pieces that fold and extend like an accordion." Military bridges that are transported by truck and unfolded to cross a gap in the terrain are examples. According to Escrig, the most important structure in this category was the Venezuelan Pavilion designed by Hernandez and Herminy and erected at the 1992 International Expo in Spain (Escrig 1996). Figure 3.4 shows a drawing of one folding member of the pavilion.

A structure that opens and closes by making use of a sliding mechanism on a mast is considered an *umbrella* structure. A familiar example is the beach or patio umbrella. Although an umbrella structure does not provide complete isolation from the environment or for the security of items stored underneath it, it is a shield against sunlight and rain.

In the 15th century, Leonardo da Vinci conceived and designed several types of *mobile structures* such as his amazing flying and war machines. More recently, Santiago Calatrava has re-invented this same concept of structure. Similar to the body of an animal, these deployable structures appear as if they had bones, muscles, and tendons, which produce smooth flowing movement across their

ranges of motion. In Calatrava's mobile structures, some space defining elements are lifted and get relocated to another position, creating a different spatial geometry and functional definition. By changing shape, the structure can be used for a different purpose. See Figure 3.5.

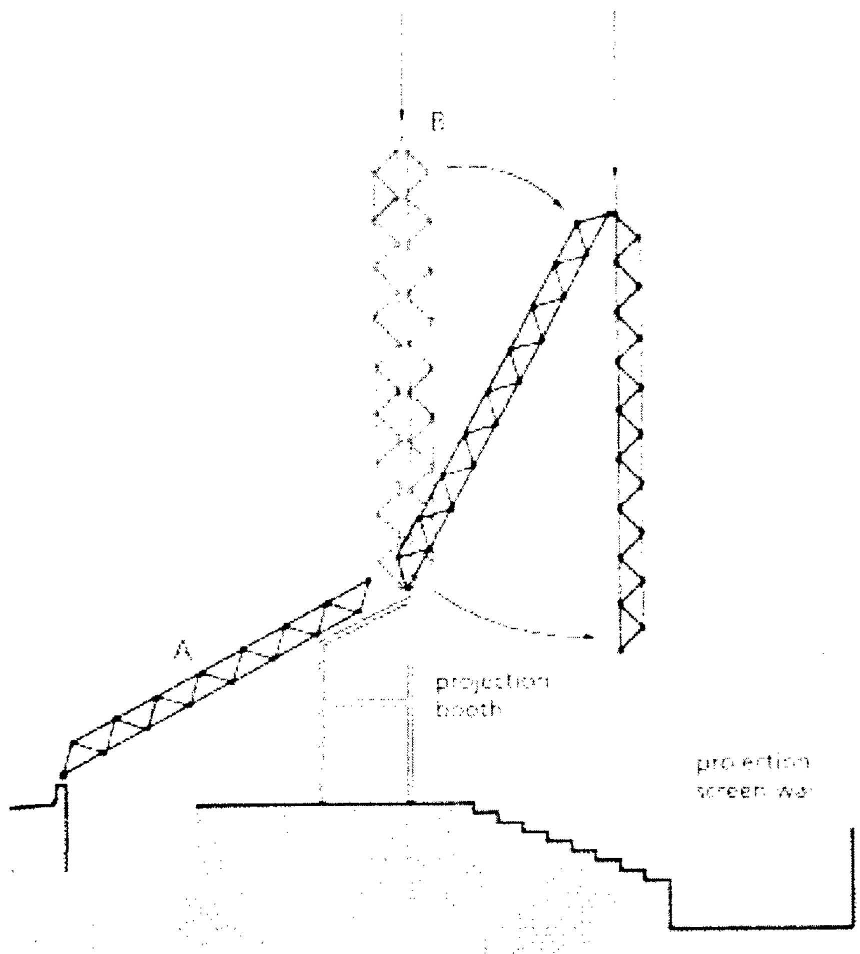

Figure 3.4 Venezuelan Pavilion from Escrig

Figure 3.5 Calatrava Mobile Structure

Lifting structures are the seventh type as organized by Escrig. These are structures that are placed at ground level then lifted into final position by an ingenious jacking system. Mamuro Kawaguchy is famous for his ingenious systems used to build large-scale roofs, such as the World Memorial Hall in Kobe, Japan. Figure 3.6 shows the building. The roof itself may not be a RAD structure or particularly noteworthy, but the lifting structure used to put it in its final position is a RAD structure.

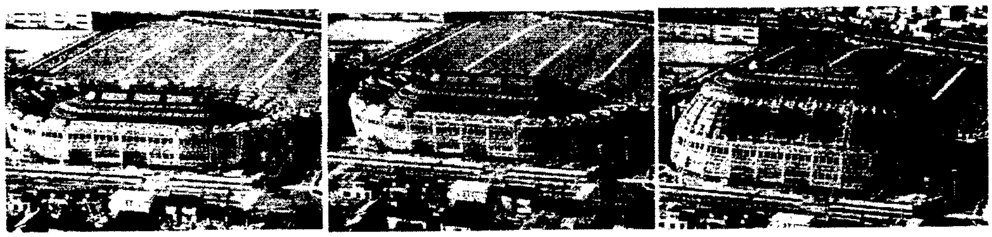

Figure 3.6 World Memorial Hall from Robbin

The last category, aptly named *deployable* for its catchall nature, includes three main types of structures not easily placed in any other category. These deployable structures have members joined at their ends in a geometry that allows for their extension and contraction. These are as follows:

- Collapsible grid structure. These have central articulating bars that are capable of being bent. See Figure 3.7.
- Un-hitched joints grid. These have bars connected to a joint allowing for even greater movement than the collapsible grid structures.
- X-frame structure. These are formed by groups of scissors with two or more arms (Escrig 1996). Depending upon the attachment position and shape of the scissor legs, the deployment may be linear or may follow a pre-calculated radius.

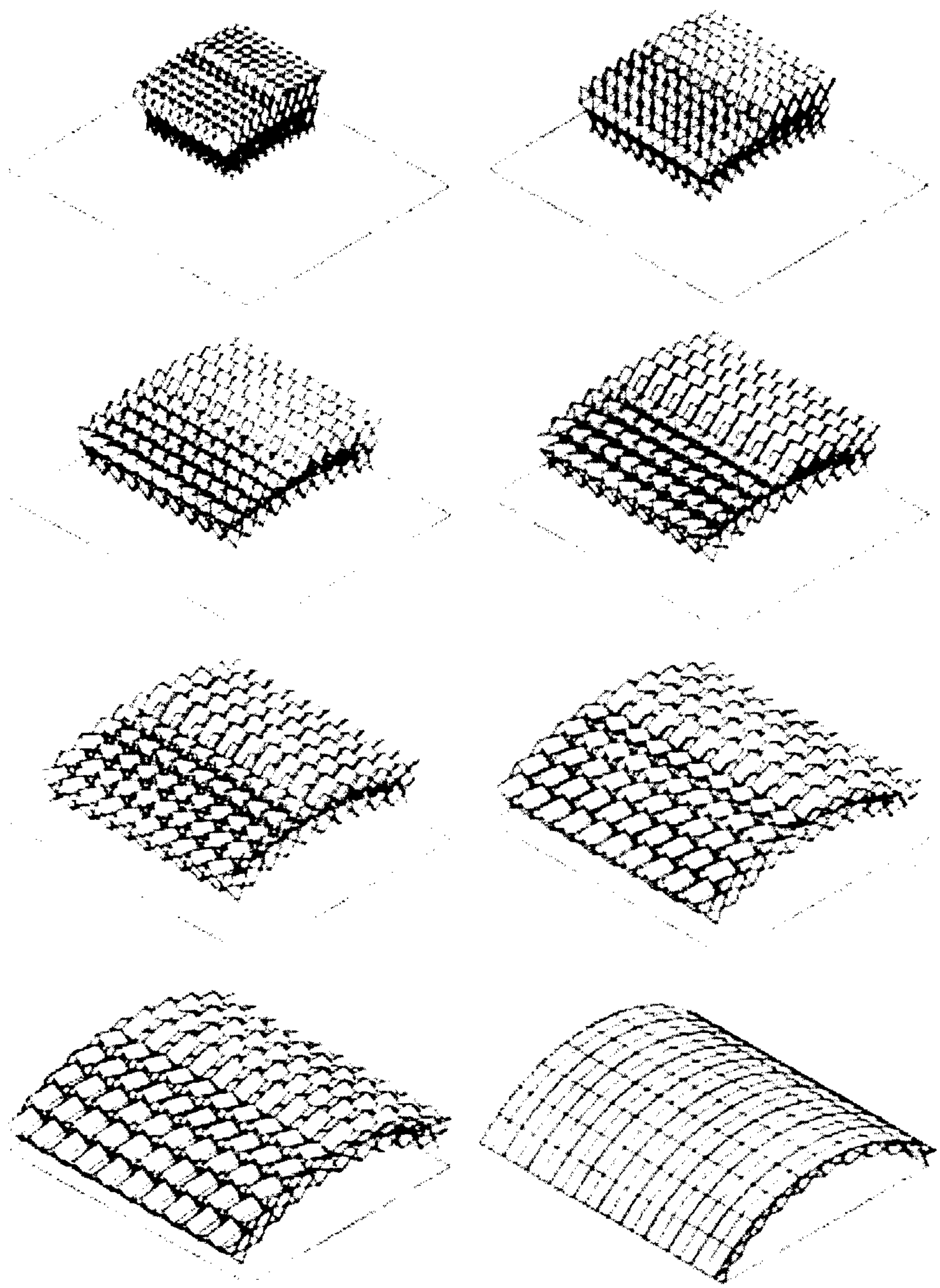

Figure 3.7 Collapsible Grid from Robbin

Escrig's classification shows the difficulty in placing vastly different deployable structures into neat categories. Structures that are in motion during normal operation and those which must be erected quickly at an unimproved site do not necessarily lend themselves to be grouped together. However, a consideration of these different types of structures is appropriate for designers and engineers when faced with meeting a client's needs for a temporary or permanent shelter, which is required immediately in a remote or inaccessible location.

3.4 HANAOR'S CLASSIFICATION OF DEPLOYABLE STRUCTURES

Hanaor offers an approach that is more methodical as compared to Escrig's, which is a general overview. His system groups the structures according to their structural-morphological properties and kinematics of their deployment, meaning that the organization is done with respect to how the structure acquires its shape and strength and how the structure is deployed. Each of these main classifications has two sub-categories, which allows for the creation of a two-way table containing four primary classes of deployable structures. See Figure 3.8.

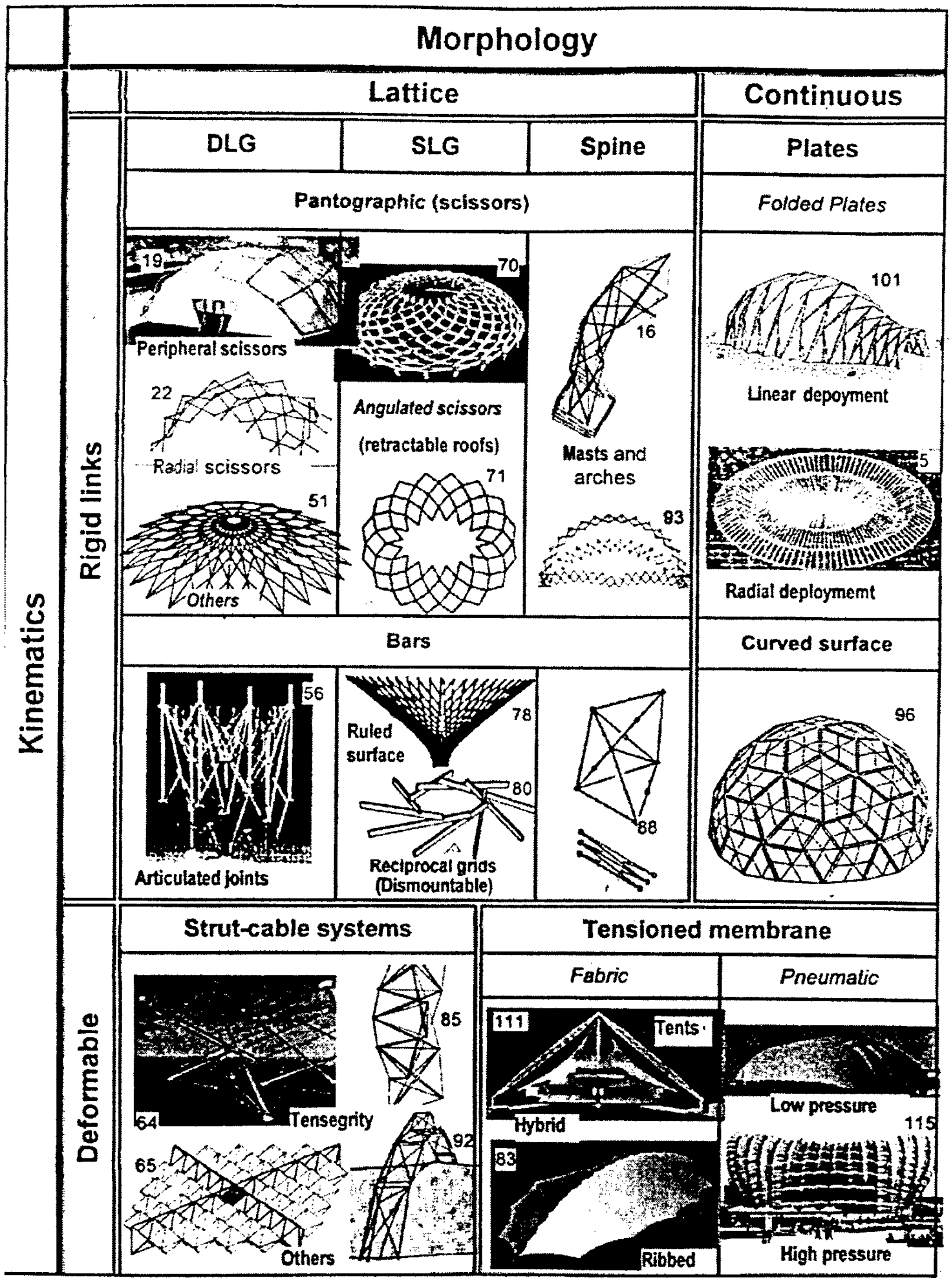

Figure 3.8 Deployable Structures Classification Chart from Hanaor

According to Hanaor, deployable structures are suitable for two types of applications: those that involve temporary structures, and others that are appropriate for use in remote or inaccessible places. When considering structures for space enclosure, as opposed to ones that simply cover an area, he evaluates them in terms of structural efficiency, technical complexity, deployment method, and stowage efficiency.

3.4.1 Morphological / Structural Features of Deployable Structures

Lattice or skeletal structures constitute the first category of deployable structures in this group. These structures rely on a structural framework to provide support and shape, which is analogous to the bones of the human body giving it form. A covering is then placed over the skeleton to complete the structure. The load is supported by discrete elements – struts, girders, beams, and columns. Hanaor breaks this category into three subcategories: double layer grids, single layer grids, and spines. Both categories of grids are made up of a regular arrangement of two- or three-dimensional structural units. Movable units, such as scissors, allow for movement from a retracted position to an extended one. Spine structures refer to structural frameworks composed of movable units organized in a linear manner.

Continuous, including *stressed-skin* structures, are the second type; in these, the surface covering itself performs the load bearing. In nature, the hard exoskeleton of a beetle or lobster acts the same way. Plates sliding against and/or

along side one another usually account for the shape in a continuous structure; fabric acts as the structural component in stressed-skin structures. These skin structures may rely on air pressure or tension in the fabric as a supporting force.

Hybrid structures combining both types of load bearing functions exist, but Hanaor keeps them separated into the two classes by handling the respective components distinctly. Examples of these types include strut-cable systems and tensioned membrane structures.

3.4.2 Kinematic Features of Deployable Structures

Structures can also be placed into two categories based upon how they are deployed. *Rigid links*, such as bars and plates, define the first class of kinematic structures. Retractable roofing systems are a good example. Involving plates and jointed members, like scissors, this category is more accurately controlled during deployment than the other kinematic category of deformable structures. One disadvantage is that increased mechanical complexity is needed to create the structure (Hanaor 2000).

Cables and fabric are examples of the deformable or soft components that characterize the second kinematic category. These pieces lack flexural stiffness so tension is required, as in the case of a tent or a pneumatic structure like a balloon frame. A prime example is the tensegrity structure, which consists of a network of bars and cables in which every bar is connected only to cables and no

other bar. Lacking any mechanical joints, the structure can be deployed either by changing the length of the bars (hydraulically or mechanically) using a telescoping system, or by pulling the cables over a system of pulleys attached to the bars (Hanaor 2000).

3.4.3 Overlapping Features of Deployable Structures

The significant aspect of Hanaor's work is showing that deployable structures must be considered in terms of their structural form together with their means of deployment. A retractable roof is a skeletal structure whose movement is done with rigid links. A tensegrity dome is also a skeletal structure, yet cables, which by definition are deformable, control its motion. A balloon frame is deformable and gets its shape from a stressed-skin covering. Even if only hypothetical, a structure can be built that has features of each category. The most appropriate type of structure is chosen based upon specific criteria.

3.5 JOCOTAS' CLASSIFICATION OF TACTICAL SHELTERS

A military application is one time where cost may not be prohibitive. An armed forces' need to shelter troops, protect equipment, and operate in many locations drives the requirement to have numerous types of structures available for immediate use. Many structures have been developed to meet these needs.

In 1975, the U.S. Department of Defense (DoD), which oversees this country's armed forces, established the Joint Committee on Tactical Shelters (JOCOTAS) to:

- Prevent the duplication of tactical shelter research and development
- Eliminate the proliferation of non-standard tactical shelters in the DoD inventory
- Maximize the usage of DoD standard family of tactical shelters

In its latest publication of January 2000, JOCOTAS defines a tactical shelter as "a highly mobile, transportable structure designed for a functional requirement that provides a live-in and/or work-in capability (JOCOTAS 2000)." It is not concerned with containers used for cargo transportation, refrigerated structures, vans, or modular/prefabricated structures that are shipped to a site and assembled by other workers. It classifies shelters into three categories:

- Rigid Wall
- Soft Wall
- Hybrid.

Rigid wall shelters are of predetermined sizes that are transportable by land vehicles, ships, or aircraft. Some rigid wall shelters are expandable while others are not expandable. All types require minimal site preparation and no specialized set-up procedures, equipment, or personnel training. Due to the lift

capabilities inherent in a military organization, the shelter is shipped in tact to the required location, connected to a generator for electric power, and is occupied and used. Figure 3.9 is an example of such a structure.

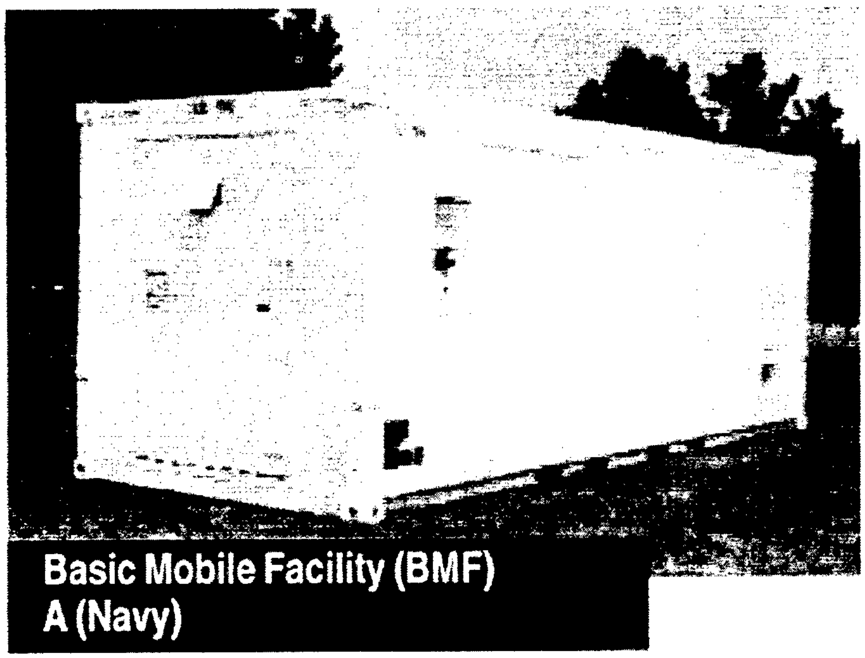

Figure 3.9 Rigid Wall Shelter

The second category of shelters is *soft wall* shelters. These air-supported and prefabricated structures are erected or assembled on site. The general purpose military tent is the classic example of a shelter to house soldiers, command and control battles, perform medical procedures, repair vehicles, and store supplies. An example of an air-supported shelter is shown in Figure 3.10.

Figure 3.10 Soft Wall Shelter

Hybrid shelters are the last category, and are simply a combination type of rigid and soft wall structure. They present no distinct characteristics. See Figure 3.11.

Figure 3.11 Hybrid Shelter

3.6 COMPARISON OF EXISTING CLASSIFICATION METHODS

RAD structures have some unique characteristics that set them apart from traditional buildings. The four classification methods discussed in this chapter are summarized in Table 3.1.

Classifier	Type of Structure	Classification Method(s)
Bulson	Rapidly Assembled	Joints
Escrig	Deployable	Materials Deployment Methods
Hanaor	Deployable	Morphology Kinematics
JOCOTAS	Military Shelters	Use Materials

Table 3.1 Comparison of Existing Methods of Classification

Bulson is the most specific of the four systems, and is only concerned with the type of joints in rapidly assembled structures. Efficiency of deployment is taken into account in his evaluation of different types of structures. Escrig classifies deployable structures according to the materials used to construct them and the method of their deployment. Hanaor also considers deployable structures, and organizes them by structural form and kinematics of deployment. He is concerned with their structural efficiency and performance. JOCOTAS is only concerned with military shelters, and classifies them according to their shape and materials.

There is no specific advantage to any of the classification systems. Because each researcher is concerned with specific applications within a vast field, each system is useful in its own area. During the development of the

parameters in the next chapter, reference will be made to structures falling within the various categories.

CHAPTER FOUR

PARAMETER PROPOSAL / ANALYSIS

It was established in Chapter Two that the user, client, and project needs must be considered and the situational facts must be known. In Chapter Three, the current classification systems for RAD structures were reviewed. To date, RAD structures are classified by their intrinsic properties with no or little regard to the needs of the users. This study attempts to bridge the gap by introducing parameters that, when considered, can lead to the best application of a RAD structure in meeting user needs and satisfying factual requirements of the function and location of the facility. This thesis proposes 59 parameters for determining an appropriate rapidly assembled or deployable structure that fall into four categories.

- Function and Use (17 parameters)
  - Basic User/Project Needs
  - Systems Integration Needs
- Contextual Response Requirements (8 parameters)
- Material Properties and Methods (27 parameters)
  - Geometric and Physical/Structural Properties
  - Erection and Collapse Procedures
- Financial (7 parameters)

The parameters residing in each of these categories and subcategories are individually explored. Examples are used to clarify the meanings. Measurements are also suggested in the text and accompanying tables to assist in accurately describing the relevance of each parameter. By understanding these issues, the decision should be influenced to select the structure that satisfies the most criteria.

4.1 FUNCTION AND USE

This group of parameters deals with the user of the structure along with the purpose for building it. It is broken into two subcategories: basic user needs and systems integration. Table 4.1 shows a summary of the parameters.

4.1.1 Basic User Needs

The *Use* of the structure is a basic parameter. A building used to shelter people from inclement weather may be fundamentally different from one used to perform maintenance on equipment and vehicles; these both may differ drastically from a structure containing office spaces used for administrative functions. Refugees seeking shelter from religious persecution have different needs from personnel on a temporary work assignment in a new location. A tensile structure providing shade from the sun and protection from rain is appropriate for certain types of storage and work activities, but it won't safely house individuals because of the lack of walls. No specific unit of measure exists for this parameter; listing the various uses of the facility and determining the square and cubic feet per person for each activity are required. Anthropometric standards need to be taken

into account for determining the minimum space that each person requires for a specific activity. The number of *Persons Living and Working* in a particular building need to be considered in order to determine the minimum amount of required space.

Function and Use	
Item	Unit of Measure
Basic User Needs	
Use of structure	cu ft, sq ft/person
Persons living and working in structure	number of pers
Security/Accessibility concerns	Y / N
Frequency of erection/disassembly sequence	every # of days
Desired erection, disassembly time	days
Expandability	Y / N
Ability to be integrated with existing structure	Y / N
Life span for application	months
Reuse	Y / N
Systems Integration	
Natural lighting	Y / N
Ventilation	H / M / L
Need for openings	#, proportion of height/width to size
Acoustical Issues	dBs
Electrical issues	KWH
Water/sewage issues	Gal/Day
Refuse	Lbs/Day
Health Considerations	Y / N

Table 4.1 Function and Use Parameters

Security /Accessibility Concerns sometimes drive what type of structure is built; other times, they are not applicable. A structure built to promote public relations at a company exhibition may provide full and open access to all interested parties. Certainly for a warehouse or maintenance shop, the necessity of large cargo doors allowing the movement of goods and equipment is logical; well-placed personnel doors also add to the functionality of a building. A RAD structure used for administrative purposes may require single locks on doors. Another structure containing sensitive computer equipment may need highly sophisticated locks, sensors, and alarm systems. Each of these needs can be met by different structures if security is considered a priority issue. For example, if vandalism is prevalent in the area, security may take on an additional importance regardless which structure is used. Otherwise, common practices will suffice.

The *Frequency of Performing the Erection and Disassembly Sequence* may be an important consideration with a RAD structure, but it is not a consideration when dealing with traditional structures. The design of the foundation and connections, for example, is completely different for a permanent structure than for one that is to be relocated once or multiple times. For both temporary and permanent structures, the weight of the structure must be considered in relation to the soil bearing capacity of the site. For a deployable structure, weight also is important for its handling and shipping configuration. If a structure is to be relocated often after being used only a short time, the sequencing of assembly and breakdown is key to efficient use. A factor

measuring the number of days between erection and disassembly captures this parameter.

Along with the previous parameter, the *Desired Erection and Disassembly Time* is not considered with traditional buildings, only the initial construction time is evaluated. However, a RAD structure may be required immediately after a natural disaster, or there may be more than ample erection time for use as in the case of a feature at a county fair. The Venezuelan Pavilion, used as an example in a previous chapter, weighed 11 tons and fit into two shipping containers. It had more than 13,000 square feet of surface area and was erected on site in two days (Robbin 1996). The time required to erect and/or disassemble the structure may dictate which structure is chosen. The number of days required for each activity would be an appropriate measure to use.

A structure that is flexible and can be enlarged or reduced in size to accommodate changing user needs is often a requirement. *Expandability* of a RAD structure is a concept not customarily addressed with traditional structures, where expansion or reduction translates to a one-time increase or decrease in area or capacity. The collapsible grid as classified by Escrig could be used in various stages of its deployment. A merchandise warehouse that can accommodate fluctuating amounts of inventory while minimizing heating and air conditioning costs may be a prudent investment. If expansion and/or reduction capabilities are

desired, sufficient attention must be given to this concept during the design or selection process.

Complementing expandability, the *Ability to be Integrated with an Existing Structure* is appropriate for addressing with RAD structures. A stand-alone structure behaves differently than if it were married to another building. Kawaguchi's lifting roof sits atop the stadium walls, which were built in a traditional method. The roofing system and access to each building are just two areas affected by integrating one structure with another. Like expandability, this parameter should be developed if integration is important.

The number of years a given facility will last, its *Life span for* this particular *Application,* can be estimated reasonably well; the length of time the facility is needed is a more evasive factor. It may be appropriate to over design the RAD structure to increase the lifespan. This would allow for additional time of use and also allow for reuse because of lower costs and the ease of erection and disassembly. Conversely, it may be appropriate to plan for the replacement of a RAD structure when a traditional structure would remain in place. This determination must be made on a case-by-case basis and be measured in months.

The *Reuse* of a RAD structure may be a key feature that drives its implementation. Due to the intrinsic properties present, a structure can be reused for similar or different functions; a fabric shelter can be used repeatedly in

numerous locations. A military bridge (pinned structure) can be disassembled, loaded on trailers, and sent forward into the battle area to be reused in the crossing of another gap. If reuse is important, then this parameter should be developed.

As discussed in the preceding paragraphs, knowing who will use the structure and for what purpose(s) logically are important for traditional and RAD structures. But aspects of the function and use have specific and important meanings with respect to RAD structures. By grouping these novel concepts, like expandability and reuse with traditional ones, the process of narrowing the field of rapidly assembled or deployable structures into a smaller field or group that meets the user's requirements can begin.

4.1.2 Systems Integration

People are the users of most RAD structures; very few structures, except for a long-term storage warehouse in a remote location, are so isolated from human contact that personal issues can be ignored. Since people are in and around the facilities, certain conditions must be present to keep them safe, comfortable, and productive. The parameters discussed in this section give proper consideration to these issues.

Ventilation and Natural Lighting are two parameters that can be addressed simultaneously. Fresh air for breathing is a requirement whether the air is naturally circulating throughout the building or is conditioned and blown by

mechanical means. A certain level of indoor air quality is necessary to allow good health, and is critical in a medical treatment facility or one where children are living. In a storage area, the lack of ventilation may be a key to proper preservation. Natural lighting allows safe and efficient work to go on and helps prevent depression; a translucent tensile structure does this. A living area normally requires a higher level of natural light than does a storage space, which can rely on electrical fixtures. Depending upon the type of work being done, workers may benefit from high levels of natural sunlight. The requirement for natural lighting and the level of ventilation needed must be accounted for during the selection process.

The *Need for Openings* is another fundamental consideration. The size and number of doors and windows are necessary in a RAD structure when there is a need for natural lighting, ventilation, and visibility. After deployment, it is difficult to add an opening to an inflatable structure but relatively easy to do so to a rigid wall shelter. Consideration of the need and placement for each type of opening is the proper way to address this parameter.

Acoustical Issues must be addressed. It may be required that a building must be insulated from the sound of the surrounding environment. Alternatively, it may be necessary to prevent the sounds of the activities occurring inside a structure from being heard outside of the structure. Depending upon the size and layout of the structure, areas within the structure may need to be separated from

other areas so that interference and carryover do not occur. If a requirement for acoustical separation exists, it would be measured in decibels.

The availability of *Electricity* is a requirement for people and structures. Electricity powers heating and cooling equipment, lights the workspace and living areas, and enables the use of other equipment such as computers, tools, and communications gear. Whether powered by generators, solar cells, or batteries, electricity is vital to the smooth operation of many aspects of modern life and business. The kilowatt-hour load drawn by the RAD structure must be accurately predicted and estimated. Due to the high efficiency of power producing equipment, overestimation of the need wastes fuel and energy, but underestimation will result in the users' demand not being met and power outages will occur. Electrical power may limit the types of RAD structure that may be chosen.

The need for *Fresh Water and Waste Water Disposal* must be considered. People require water to drink, for cooking, and for personal needs, and some machinery requires water for operation or cooling. The effluent generated from these needs to be disposed of in a sanitary manner through an existing sewage system. It can be collected and transported off site, or piped into a leach field. It must be determined if a water system is to be integral to the structure or if water bottles or water trucks will be used. Fresh water may be available from a well, spring, stream, or existing water system; sometimes water must be delivered to

the site. Measured in gallons per day, the amount of water required and wastewater produced is information necessary when designing or selecting facility.

The collection and disposal of *Refuse* is important in the overall planning effort. An office space or living area generates a certain type and amount of waste; an eating facility and maintenance area generate different kinds and usually much more waste. A location downwind and removed from the main area is desired for accumulating the refuse and if necessary, operating a landfill. The waste, measured in pounds per day, must be collected and disposed of properly which includes the sale, recycling, burning, burial, or hauling away.

Health Considerations is the most important parameter in this subsection. A RAD structure that inhibits the growth of mold and bacteria, can easily be thoroughly ventilated, and allows for good sanitation practices is the type that is needed. A well-sealed and well-maintained structure is significant in the effort of controlling pests and rodents; a rigid wall shelter acts like a traditional structure in this instance. The use of an Industrial Hygienist, who is educated in making a facility safe for human habitation, is necessary for addressing this issue.

Since people occupy most RAD structures, the buildings require electrical power and water. Ventilation and light are two other parameters whose impact can be underestimated. People generate waste of various types, and their health

must be protected. The parameters discussed above necessary for giving the proper attention to such issues when a RAD structure is employed. The structure failing to meet the minimal standards of such issues will unnecessarily risk the welfare of the people who use it.

4.2 CONTEXTUAL RESPONSE

The previous section presented parameters that were concerned with the function and use of a rapidly assembled and deployable structure. These parameters are important in creating a facility that meets the requirements and needs of the user. Now the focus widens to consider the context of the facility and site itself, which are the facts of the situation and must be analyzed according to the design logic presented in Chapter Two. Consideration of the context will verify that the RAD structure is appropriate for this particular situation. Table 4.2 summarizes the parameters associated with context.

Contextual Response

Item	Unit of Measure
Cultural Dependence	H / M / L
Climatic/Microclimatic Considerations	H / M / L
Area preparation/Site work/Foundation required	W-H
Grade of site	% slope
Limited or specific footprint	Y / N
Contamination/Hostile environment	Y / N
Range of internal temperature of structure	degrees F
Site Accessibility	H / M / L

Table 4.2 Contextual Response Requirements Parameters

Cultural Dependence relates the building to the community in which it exists and the people it serves. The culture of a city or country may be so restrictive that only certain types of structures are acceptable; the exception to this may be in the event of a natural disaster, when anything would be welcomed. There may be a need to use only local materials, particularly if the native people are skilled working with them, and the site is remote. The use of specific shapes or forms of RAD may be important to the religion or traditional way of living. Renzo Piano designed a cultural center in New Caledonia that looks like the traditional grass huts built for generations; his structure respects the local people and dignifies their history. The aesthetics of a structure is captured by this parameter. An oil company on a drilling site chooses a structure that is inconspicuous and promotes positive reactions by the local inhabitants.

The *Climatic/Microclimatic Considerations* in which the structure will be built is a fundamental consideration. An arctic environment requires a different approach than a temperate one; a desert has different characteristics than a tropical rain forest; the coastline is different than mountains. In harsh climates such as the arctic, a mobile structure that is speedily erected has distinct advantages over a traditional building. Statistical weather data is now available for virtually all areas of the world, and can be used for predicting future conditions. The level of precipitation, altitude, and wind load (discussed later in

the geometric and physical properties subsection) all can significantly shape the decision in the selection of a structure.

Area Preparation, Site Work, and Foundation required for the RAD structure need to be considered. Trees and brush may need to be cut to create a firebreak or allow a building to be built. The area may require clearing of debris and grubbing of vegetation. In certain types of soil, fill may be needed to stabilize the soil or piles may be driven. A concrete foundation may be the most appropriate method of securely anchoring a facility; alternatively, such a site disturbing activity can be avoided by using certain RAD structures like tensegrity structures. Research is ongoing by P. Fisk at the Center for Maximum Potential in Austin, Texas, into foundations that are augered into the ground instead of constructing typical concrete footings. When the need is gone, the shafts are removed and minimal work remains for site restoration. Aesthetics, although not a driving force for designing the facility, is considered for landscaping and lighting to enhance the appearance of the area. The work hours to complete these activities must be accurately estimated so that a realistic selection can be made.

Another aspect of the site to consider is its *Grade*. The slope may allow particular structures to be built only with extensive earthwork. A steep slope in rocky soil may be less restrictive than the same slope in heavy clay soils. In some climates, rainwater runoff is an issue that must be addressed to prevent constant

flooding and limit infestation by insects. Knowledge of the percent slope and contours of the site is needed to have a facility properly sited.

The two parameters dealing with site preparation and grade lead to another parameter addressing whether or not a *Limited or Specific Footprint* is needed. A plot of land in a dense jungle is probably much more restrictive than an open field in the grasslands. An urban lot may be in close proximity to electrical power and water, but is limited in the amount of expansion that can take place. The structure may have to fit between two natural items, such as old growth trees or rock outcroppings. Minimizing the footprint of a structure may be done to limit the environmental impact of a facility.

Living or working in a *Contaminated or Hostile Environment* presents unique challenges. Facilities erected for the response team to an oil spill or chemical plant accident must provide the workers with a clean area. For military applications and some specialized civilian operations, the structure may have to protect against electromagnetic interference or an electromagnetic pulse. An impervious barrier must exist during a chemical, biological, or radiological attack so personnel are adequately protected; a self-contained inflatable shelter used by the U.S. military insulates troops from the fatal effects of exposure. A facility erected near heavy fighting or in a high crime area may require special locks, windows, and extra-stiff walls. A hostile or contaminated environment can drive many basic decisions about a RAD structure.

The *Range of the Internal Temperature of the Structure* dictates whether special equipment is needed to condition the space. Maintaining a particular range of internal temperature also involves insulating the walls, roof, and windows. People living and working in a structure typically perform better and are more comfortable with temperatures from about 65 to 75 degrees Fahrenheit. If the structure is used only as a controlled climate storage space, the range becomes wider, subject to the characteristics of the stored goods. General storage space does not have specific requirements and is subject to natural conditions present in the area.

The last parameter in this subsection deals with *Site Accessibility* to the RAD structure. A United Nations relief facility may have refugees passing through on foot; it may be necessary for a suburban or urban site to accommodate people and vehicles and the effects of public transportation. An isolated and remote site without modern transportation faces different dilemmas than a congested one near a city. When the facility is being erected, the construction equipment and materials must be able to be brought on site. The facility must be able to be re-supplied and serviced. The collapsible grid offers two of the four sides as unrestricted access for visitors and workers. And if the facility is to be dismantled and redeployed, the temporary accessibility may need to be stopped so the site can recover and possibly revert to its natural state.

The examples that are discussed illustrate how the situations when a rapidly assembled or deployable structure can be used differ from traditional applications. A tensegrity roof, as identified by Escrig, may require less site work than a traditional building, but it is useless in a contaminated environment. A hard-walled shelter would protect against the contamination, yet would not fit in with some cultures and must be served by a noisy heating and air conditioning system. The selection must be made according to the prioritized needs of the user in conjunction with the reality of the site.

4.3 MATERIAL PROPERTIES AND METHODS

Whether a building is made of bricks and mortar, metal skin pinned to steel members, or fabric stretched over a geometric framework, the materials that make up the structure help determine how the building performs structurally. The materials and the method of assembly are of critical importance in the design or selection of a RAD structure that is expected to fulfill a specific need at a specific site.

Already having discussed the function and needs of the user and the context of the structure, the third grouping of parameters is divided into two subcategories: geometric and physical properties, and erection and collapse procedures. The section titled geometric and physical properties contains parameters dealing with the size, weight, design criteria, and maintenance of the structure. The erection and collapse procedures section is concerned with the

personnel who assemble the structure and the methods they use. Table 4.3 shows these material properties and methods parameters.

Material Properties and Methods	
Item	Unit of Measure
Geometric and Physical Properties	
Structural system	self-supported or skeleton
Minimum and maximum size of structure	SF / CF
Minimum and maximum size of usable space	SF / CF
Equipment integrated into structure	Y / N
Fire protection	H / M / L
Storm considerations	H / M / L
Seismic/Volcanic considerations	H / M / L
Windloading	H / M / L
Snowloading	H / M / L
Mobility of structure in compact form	H / M / L
Weight and Volume	Lbs / CF
Off the shelf or engineered for this particular use	Y / N
Delivery time	days
Capable of withstanding long term storage	Y / N
Maintenance required during storage	W-H
Maintenance during deployment	W-H
Reconstitution effort	W-H
Part replacement	H / M / L
Erection and Collapse Considerations	
Safety of workers and public	list each item/area
Project Management	H / M / L
Plans and Specifications	H / M / L
Float	H / M / L
Level of assembly	H / M / L
Collapse method	H / M / L
Work hours to erect/disassemble	W-H
Skilled & non-skilled workers required	# of workers
Special tools & equipment required	Y / N

Table 4.3 Material Properties and Methods Parameters

4.3.1 Geometric and Physical Properties

One of the first considerations in choosing the space defining elements that enclose the users of a RAD structure is the *Structural System* that will be used for the construction or assembly. Soft materials, like fabric used for roofing, cannot support themselves and must rely on a skeletal structure for shape and form, unless they are placed in tension. They also deform or break easily when subjected to point loads like falling rocks or user loading such as suspending shelving or other necessary finishes from the walls or ceiling. Hard materials, such as metal plates, are load bearing and sturdy; they can support themselves and offer protection against point loads. The determination of using self-supported materials or a skeletal system is necessary.

From an engineering viewpoint, these structures must support their own weight and their live loads in one or more geometric configurations. They must also acceptably perform when subjected to various loads. A traditional structure subjected to wind loads will lose its roof before being uprooted or shifted. Assuming high strength fabric is used, a tensile structure will simply be blown away from its foundation. Personnel may not be able to walk on the roof of an inflatable building, nor can antennas be mounted into the material. Bulson's classification system focused on joints; the most research done to date has been on scissor structures. Their joints must be strong enough to withstand the various stresses imparted during movement (Liapi 2001).

The *Minimum and Maximum Size* of a RAD structure results from the function of the structure as well as the system used to hold the structure together. In addition, as with traditional structures, it may be important for the structure to be seen as a focal point from a great distance, or it may be desirable for the structure to blend well with the surrounding landscape. Due to site location, fitting the structure under the tree line or an adjacent roof overhang may be necessary. Conversely, the structure may need to rise above its surroundings affording a view of the area. Measured in square or cubic feet, the size of the structure sets the limits of the facility.

The size of the overall structure drives the *Minimum and Maximum Amount of Usable Space* available and determines what occurs and what can be placed inside it. Office spaces and living areas for temporary workers require a different ceiling clearance than workspaces used for performing maintenance on aircraft; the collapsible grid has much excess space for office workers. Warehouses typically use minimal floor space and take advantage of shelving systems to store goods. And highly configured spaces used as offices are different than large meeting rooms and assembly areas. Even if the user cannot define the needs and requirements in terms of square or cubic feet, the requirements must be translated into a facility of adequate size.

Any hydraulic, pneumatic, electrical, and mechanical *Equipment Integrated Into the Structure* requires particular attention. If the climate or use is such that air conditioning or heating is required within the structure, an early decision must be made to incorporate the systems into the structure or have them be add-ons at a later date. If wiring is needed to facilitate lighting and computer networks, it can be placed within the walls, ceiling, and floors or run exposed to the user. Any hydraulic or pneumatic system necessary for movement or deployment of an item such as a retractable roofing system or movable canopy should be considered when designing the structure or evaluating an existing one. In some cases it may be worthwhile to have doors, windows, and shelving be part of the structure itself. Shelving and suspended ducts or piping cannot be integral to a sliding structure where plates overlap each other. Other scenarios may dictate that items such as these be external to the facility, stored separately, and attached after the structure is fully deployed. If no equipment is needed to meet the needs and requirements of the user, the issue is not addressed.

Fire Protection and Storm Considerations (precipitation and flooding) must be considered. Administrative workers using a temporary shelter require a minimal amount of protection from fire; skilled workers using hazardous materials require extensive protection. A fire sprinkler system is not required in temporary buildings, but smoke detectors, alarms, fire extinguishers, and escape ladders are prudent items to provide. Since much of the world's population lives

in littoral regions, the affects of water must be anticipated. Whether or not local building codes are applicable must also be considered.

Seismic and Volcanic Considerations, and Wind and Snow Loading are addressed as applicable to the region. Depending upon the area in which the structure is sited, it may be possible to ignore seismic and volcanic issues due to the relatively short intended lifespan of the structure. However, in the case of responding to a natural disaster of a volcano erupting, structures resistant to acid rain and the infiltration of airborne particulates perform better than other ones. Environmental loads due to wind and snow are produced in areas with moderate winds and snowfall. Wind or snow and rain mandate a weather-tight RAD structure for the protection of people, equipment, and merchandise.

The *Mobility of the Structure in Compact Form* is a requirement specific to RAD structures. Depending upon the circumstances, a foldable structure may have to fit on the bed of a tractor-trailer for easy movement to the site. The structure may need to fit on an aircraft pallet or within an aircraft-shipping container for airborne delivery. The main components of the structure may have to fit inside a standard shipping container for trans-oceanic movement. A structure that can be moved by hand is handled differently than one that must be moved by forklift or crane around the site. Some expeditionary military bridges are directly set across waterways from the trailer of a truck. A hinged structure with multiple joints may be damaged more easily when compared to a plated one

that can withstand rougher handling. The importance of mobility in meeting the requirements of the customer needs to be determined.

Weight and Volume is a key issue for a deployable structure. As discussed above with mobility, a structure that fits inside an airplane or on the bed of a truck may be preferred to one that needs special consideration for movement. The weight of a deflated structure is comparable to one that is inflated, but its volume is drastically different. A temporary building in an urban setting might have few restrictions as compared to a building required in a rural or remote setting. Pounds and cubic feet are standard units for measuring this parameter.

Whether a structure is available *Off the Shelf* or needs to be *Engineered for this Particular Use* is an issue valid for both traditional and RAD structures. A tent canopy readily available from a party rental service may be a better, cheaper solution than creating a "make shift" covering for a celebration. A company owning collapsible buildings used during promotional sales events understands the benefits of having its needs satisfied by an off the shelf product. It is also possible that the company specifically had these buildings designed and manufactured for its particular application and now reuses the structures to take advantage of the initial investment. A new structure may be too expensive to design and build. If an off the shelf product exists that meets the needs and fits the site, it should be considered.

The *Delivery Time* of the RAD structure is important when using off the shelf products or responding quickly to an exigent requirement. Being able to provide shelter and storage space rapidly could save human lives and limit material damage. In preparation for an emergency, the structure may have been pre-staged and simply requires delivery on-site. Possibly an indefinite delivery contract is in place with a qualified vendor and a delivery order is placed to obtain the low-pressure pneumatic structure. In a worst-case scenario, the emergency is completely unforeseen and no prior planning has been done; then the quick response time of industry must be relied upon. Delivery time of parts and materials is important in regular construction projects; the need is exacerbated in an emergency when swift action is required. The number of days is the most logical method for measuring delivery time.

A RAD structure that is *Capable of Withstanding Long Term Storage* may be invaluable. Fabric dry rots, wood warps and rots, and metal rusts. A structure that is impervious to these natural occurrences has significant advantages. A structure, broken down into its component parts or in its compact form and stored indefinitely until the moment it is needed, offers great flexibility. Climate controlled storage is one way to decrease the decay of fabric, wood, and metal. Another possibility is minimizing the use of these materials. Vendors can assist in the analysis of the components since they usually have access to research and performance information not necessarily available to others.

Congruous with a capability of withstanding long-term storage, the *Maintenance Required During Storage* is a facet often overlooked. A very useful structure is one that, with minimal maintenance, is capable of being utilized multiple times or on short notice. A simple action like joint lubrication may be all that is required to keep a stored scissor structure in good working condition. Other RAD structures with hydraulics may require unpacking and full erection to exercise fluids and keep seals supple. The maintenance required during storage, measured in work hours, can significantly add to the effort and cost of having a RAD structure readily available, but it may be necessary if the expected delivery time cannot be met any other way.

The *Maintenance During Deployment* of a RAD structure, captured in work hours just like any other maintenance, has some different characteristics when compared to traditional structures. Joints always require lubrication and cracks must be caulked. But the exterior wall does not need painted on a fabric structure; the fabric needs replaced; in inhospitable climates, this can be difficult. Movable parts need exercised to prevent hinges from locking and seals from rupturing. With components that are hard to manufacture or find, it may be pragmatic to have replacement parts on hand. If the deployment is temporary, maintenance may be postponed. However, if the structure is going to be repacked and deployed to another location, the best time to perform certain aspects of maintenance, like a visual inspection of the entire structure, is when it is fully deployed.

Restoring an assembly or structure to its former condition is called *Reconstitution*. The effort in performing activities like airing fabric to prevent mildew, cleaning equipment, replacing damaged wooden items, greasing pins, and re-certifying structural elements is necessary when storing a structure in preparation for redeployment. Measured in work hours, the amount of this work is typically underestimated. For the military, it takes tremendous effort to make deployable gear and equipment used in the field ready for use again. The same is true for organizations repeatedly using RAD structures on a periodic basis. Whether placed in temporary or long-term storage or simply moved to another site, the reconstitution of deployable structures deserves consideration.

Consideration should also be given to the level of *Parts Replacement* for a RAD structure. Whether during deployment or reconstitution, if replacement parts are available locally or from the manufacturer, or can be created from standard materials readily obtained, the process will go smoothly. Replacement pins and hydraulic cylinders are easier to procure than foldable joints. Workers may inadvertently break or misapply components. Components may wear out with continual use. Replacement parts, which are easy to obtain, add flexibility to the structure and provide an extra level of insurance to the user.

Overall, the geometric and physical properties of a RAD structure deserve substantial consideration. In a moveable structure, the geometry of the structure may change on a regular basis (for sporting events) or less frequently (with the

seasons of the year). There are many issues, from the properties of the materials used, building code considerations, maintenance, and assembly that need to be examined. In some countries standards of the International Standards Organization (ISO) are applicable and require investigation. If these standards are not met, a structure will be unacceptable and cannot be built.

4.3.2 Erection and Collapse Considerations

Another subdivision of the material properties and methods category considers the procedures for erecting and collapsing the RAD structure. Some of these parameters are non-existent in traditional structures. If deployed on a recurring basis, the efficiency of the procedure can be observed and easily analyzed. This includes the number of workers used and the length of time required.

Safety of the Workers and the Public is always of paramount importance during any construction undertaking. Workers benefit from a comprehensive safety plan listing the hazards and measures that reduce risk. The elimination of risk is desired. Protection of workers may include specific safety tools and equipment such as goggles and scaffolding. The public will be kept safer with the use of temporary fencing and well-placed signage. Awareness of safety issues allows people to work efficiently and minimizes the risk of injury.

Attention must be given to the *Project Management* of the structure. The general foreman must be capable of managing the safe and efficient completion of the project. Proper scheduling of workers and material deliveries, controlling costs, and efficiently managing the activities are crucial to making the project a success. Interfacing with the customer, user, and local officials must always occur throughout a project. Because conditions, information, and requirements may change often in emergency situations, closer than normal coordination is required for those projects, which are more likely to involve a RAD structure.

The *Plans and Specifications* necessary to assemble, disassemble, and re-deploy a RAD structure are necessary for the transformation of an idea into a physical reality. Availability of details in the form of plans and specifications, shop drawings, or an assembly manual may be of critical importance for the structure selection especially if the structure presents a high level of geometric complexity. The concept of the construction may be presented on full size drawings or on a few sheets of paper, depending upon the pre-assembly level and of the availability of support personnel. If the facility is simple enough, like a bridge that needs to be unfolded, it may be possible that the construction method is self-explanatory.

The concept of *Float* is concerned with the amount of extra time available in a schedule. This time, tracked in workdays, can either be between the proposed completion date and the date when the structure is actually required, or it can be

with respect to non-critical activities that are completed concurrently with the critical activities. During an emergency response scenario, float may not be an issue, because all things need to happen as soon as possible. Even in this case, some decisions and activities can be delayed until as late as possible, waiting for the latest information and assessment. For the planned use of a RAD structure, float can be considered just like it would be for a traditional structure.

The *Level of Assembly* is particularly important when considering the amount of time that is takes a structure, once on site, to be fully functional. In a typical environment when the use of a temporary structure is planned for, the level of assembly may be low and be no real concern. In another environment where exposure to toxic chemicals is lethal, the level of assembly (i.e. the amount of time workers are particularly vulnerable) is absolutely critical. When a facility is urgently needed, as in wartime, a high level of pre-assembly is desired to meet the compressed schedule. In another instance, in a developing country with few skilled workers, it would be beneficial to have a building that requires minimal assembly.

A scissor structure is a good example of a structure that is basically extended and fastened into place. There is virtually no assembly. A hinged or pinned structure, as classified by Bulson and discussed in the previous chapter, would also satisfy the requirement for a structure having a high level of assembly. A hinged structure may be unfolded and set in place, and used immediately. A

pinned structure may need to be bolted together but still can be functional much more quickly than a structure built of its component parts. When the requirement for construction speed is high, other factors become secondary considerations and the requirements for pre-assembly rises.

Possibly more important than the method used to erect a facility is the *Collapse Method* used before relocation or storage takes place. With examples similar to the ones presented above concerning the level of assembly, the collapse method may take on extra significance in a hostile or toxic environment. Workers not having coordinating instructions or proper training on how to break down the structure may damage a facility. Improper packing may submit the structure to unnecessary reconstitution effort, damage during transportation, or render the structure completely unusable. The efficiency of the method used to collapse the RAD structure must be well developed unless the components are to be discarded after being disassembled. Due to the temporary nature of some applications, this parameter may override other criteria for mobility, speed, long-term structural stability, and expandability.

The number of *Work Hours to Erect/Disassemble* the RAD structure is an obvious parameter. A structure as simple as a tent may require only a few hours to erect, but a tensegrity roofing system may take a few weeks to build on site with no pre-assembly. A structure with a high level of assembly can be dismantled relatively quickly. When dealing with a rapidly assembled structure

that is required immediately, knowing the erection time is critically relevant to meeting the user's requirements.

The need for *Skilled or Non-skilled Workers* may drive the type of structure considered. Highly skilled workers may be required, when the level of assembly is relatively low, to assemble steel or composite members into a working structure. Other times, unskilled workers may be capable of making a few connections or cover a skeletal structure with fabric. This may be advantageous in a developing country where native workers are readily available, especially when the requirement for shelter is due to a natural disaster. On site training may be necessary to equip the workers with the capabilities to erect or disassemble the RAD structure. The U.S. military, subscribing to the JOCOTAS classification of shelters, uses troops with specialized training to erect the shelters needed for military operations. Knowing the type of each worker and training needed will satisfy this parameter.

Special Tools or Equipment presents additional requirements. Any electric, pneumatic, or hydraulic tools (e.g. power saws and drills, welding torches, mortar mixers) must have a power supply, adequate safety devices, replacement parts, and, for some, replacement units. Some of the components of the structure, as well as some tools and equipment, may need complementary equipment to become fully effective; a trailer and forklift might be needed to provide a generator and move items as necessary, and a crane could be used for

finishing a roof. In certain situations, it may be more appropriate to limit the amount of equipment used and have more workers on site to reduce the environmental impact and need for heavy machinery. The Bailey bridge, developed in Great Britain and used since World War II, relies upon no mechanical advantage. Troops are able to move the components and pin them together by hand. For all these tools and equipment, the workers must be trained in their safe and proper use. Constructing a RAD structure may produce additional requirements not usually considered during a traditional project.

The parameters dealing with the erection, collapse, and general construction of a RAD structure capture the same concepts that are followed daily on construction sites, but they have a different focus. The collapse method is an important consideration for deployable structures that doesn't exist for traditional structures.

4.4 FINANCIAL

The function and use, the context, and the material properties and methods of rapidly assembled and deployable structures have been addressed in the previous three sections of this thesis. The remaining group of criteria deserving attention deals with the associated monetary issues. These parameters could have been included alongside the technical ones already presented, but justify a single grouping separate from the others.

Table 4.4 lists the financial parameters of concern when addressing a RAD structure. As discussed previously, many are the same whether the structure is traditional or RAD; the difference lies in the interpretation and details.

Financial	
Item	Unit of Measure
Material/Purchase cost	$
Deployment cost	$
Erection cost	$
Maintenance cost	$ / month
Disassembly cost	$
Reconstitution cost	$
Storage cost	$ / month

Table 4.4 Financial Parameters

Overall *Cost* is typically the overarching financial consideration for a structure. A deliberately planned project has a detailed budget to monitor and control costs. If an immediate and unplanned requirement develops, the funding authority may set broad guidelines and place a cap on the spending, relying on the judgment of subordinates. The complexity with respect to a RAD structure lies with the consideration given to reuse; different materials may be specified and the lifespan increased. Extra money may be spent on features, which allows for easier transportation, assembly, or movement of the components. A plan can be formulated so that the structure is replaced before the need for the structure goes away. The components of the overall cost can be broken down as follows:

- *Material/Purchase Cost* – this cost covers the outright purchase of a structure or of the materials required to build a RAD structure from its component parts.
- *Deployment Cost* – this cost includes shipping the structure to the site. Also included would be fees incurred and permits required during the transportation.
- *Erection Cost* – this is a total amount of money required to pay for workers, safety items, tools, and equipment needed. Site preparation and any required building or environmental permits are included.
- *Maintenance Cost* – money spent on recurring or specific components, tests, calibrations, and work necessary to support a fully functioning facility. This is the cost to operate the facility on a regular basis. Also included are costs that might be higher due to the use of a RAD structure. For example, a balloon building would have higher heating and cooling costs due to the lack of insulation.
- *Disassembly Cost* – considers the payment of workers, safety items, tools, equipment used to dismantle the RAD structure, and returning the site to its original condition.
- *Reconstitution Cost* – is money spent to prepare the structure for long-term storage or redeployment. It includes the replacement of damaged items and re-certification of critical elements. This

includes the shipping cost from the deployment site to the storage or next deployment site.

- *Storage Cost* – considers the amount of money required to store the structure before its initial use or in-between uses. Also included is any money required for maintenance during the storage period.

All these parameters can be included in the financial analysis of the project. The life cycle cost of a rapidly assembled and deployable structure would normally be compared to a traditional structure to gain an appreciation of the differences in using either approach.

The numerous parameters discussed throughout this chapter form the basis for selecting the most appropriate rapidly assembled or deployable structure from the types presented earlier. They are detailed to stimulate thinking and allow for full development of the project. They are also general enough so that the particulars of the scenario can be adequately addressed and additional parameters considered. They fit into the logic of determining the needs of the user and the facts of the situation. Designing a facility and addressing the needs and requirements of a user is not simply done by completing a checklist; rather, the situation must be evaluated to determine which issues are critical, important, ordinary, or can be ignored or assumed away. The value in presenting such a

comprehensive list is in providing a starting point from which the facts can be researched and a workable result produced.

CHAPTER FIVE

CASE STUDY

The previous chapter identified and organized parameters into groups, using the logic reviewed in Chapter Two and providing examples from existing categories of structures reviewed in Chapter Three, that assist in the choice for the most appropriate rapidly assembled or deployable structure. Parameters were organized into four categories with regard to the intended use of the structure, the built or physical context in which it will be constructed, the materials and methods used for its implementation, and the cost to complete all the activities. In order to show the benefit of this method of organizing parameters, a case study is now presented. After establishing the realistic scenario, data will be entered into the tables created in Chapter Four. Finally, some conclusions will be drawn to show the usefulness of the parameters in selecting a RAD structure based upon the issues and priorities presented.

5.1 PROBLEM DESCRIPTION

Texas annually holds its State Fair in Dallas. Drawing people from numerous cities and walks of life, the organizers aim to create an atmosphere for fun as well as learning. Structures are needed to protect displays and people from the sun and rain of September and October. Large covered spaces are needed for various purposes such as an arena, dance floor, and a children's play area.

Smaller spaces are needed for display booths that advertise products and services, conference rooms are required for educational classes and meetings, and administrative areas are needed for offices as well as storage areas. The promoters could use traditional structures to meet all their facility needs; they have considered using RAD structures for the area needed for educational activities. The needed space for educational activities is approximately 12,000 SF and is broken down as follows:

Requirement	**Space**
Classrooms	5,000 SF
Multi purpose area	1,000 SF
Children Play Area	2,000 SF
Administration	4,000 SF
Total	**12,000 SF**

Using RAD structures brings some added creativity to the fair and showcases new technology and the talent of local construction professionals. These newer structures offer added visibility to the educational area by attracting people of all ages.

5.2 COMPLETION OF PARAMETER TABLES

In Chapter Two it was shown that a choice is based on acquiring information, creating options, and evaluating the options to make the best choice. It was also shown that goals, facts and user/client/project needs were first to be considered in the design process. In this scenario, fact gathering has determined that goals go beyond the use of the structure and issues like project visibility,

funding options, appropriate site features, and site analysis of possible locations need to be taken into account. These goals must be understood before the specific project needs are determined.

The first level of analysis has determined that two basic options exist: one large structure housing all the educational activities, or smaller structures varying in size for each particular activity that are connected by temporary sidewalks or breezeways. Figure 5.1 shows a conceptual drawing of the two options available. It is possible that the same type of structure in different sizes could be used in Options One and Two. For Option Two, Type A structures are larger and different than Type B structures. Since Type B structures are smaller, additional structures can be added to expand the covered area; dashed lines in the drawing denote this.

The basic analysis has helped in completing the tables shown throughout this section. Table 5.1 lists the "function and use" parameters as determined for this scenario. The first two columns do not change from the tables presented in Chapter Four; columns three, four, and five are added. Column three entitled "Option One - 1 type of RAD" represents the scenario if only one type of RAD structure is used. Column four entitled "Option Two - 2 types of RAD – Type A" shows information specific to using the larger (Type A) of two different types of RAD structures. Column five contains information specific to using the smaller (Type B) of two different types of RAD structures and is entitled "Option Two - 2

types of RAD – Type B." The information in columns four and five sometimes differs from column three since the requirements for the activities that will occur in the two types of structures are different. Offices and classrooms have different requirements that a multi-purpose room and indoor play area.

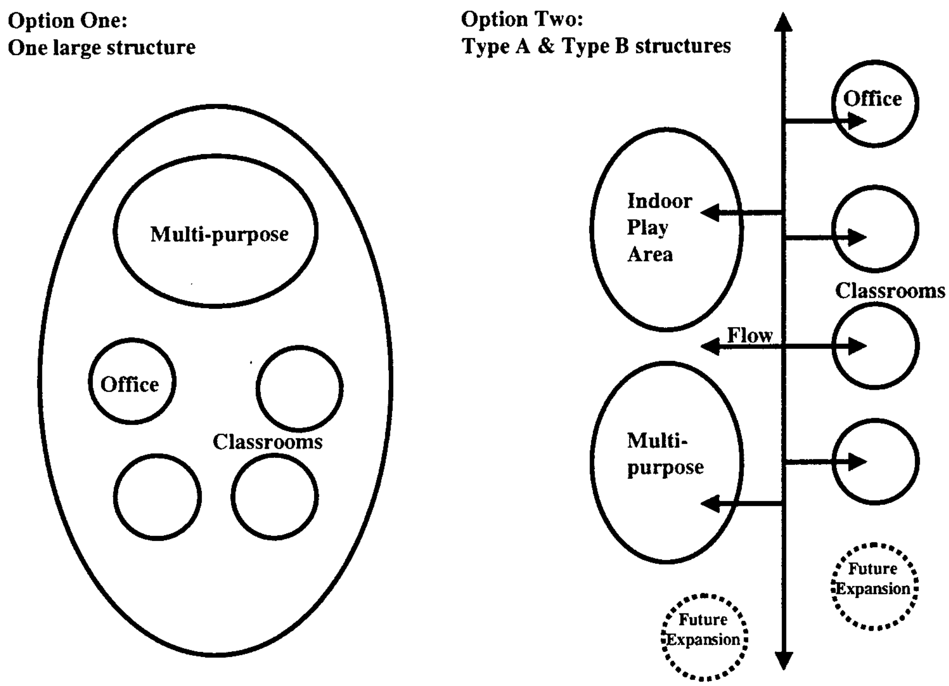

Figure 5.1 Two Options of Meeting Educational Activity Requirements

Function and Use				
		Option One	Option Two - two types of RAD	
Item	Unit of Measure	1 type of RAD	Type A	Type B
Basic User Needs				
Use of structure	cu ft, sq ft/person	Classrooms, Offices, Multi purpose	Multi-purpose, Indoor play area	Classrooms, Offices
Persons living and working in structure	number of pers	Up to 100 visitors Up to 25 staff	Up to 50 visitors Up to 12 staff	Up to 50 visitors Up to 12 staff
Security/Accessibility concerns	Y / N	Limited access for public's protection	Open access	Limited access
Frequency of erection/disassembly sequence	every # of days	One time setup	One time setup	Setup multiple times
Desired erection, disassembly time	days	Two weeks	Two weeks	Two weeks
Expandability	Y / N	No	No	Yes
Ability to be integrated with existing structure	Y / N	Yes	Yes	Yes
Life span for application	months	2 months	5 years	2 months
Reuse	Y / N	Structure remains on site or is relocated	Remains on site	Relocated to another site
Systems Integration				
Natural lighting	Y / N	Yes	Yes	Yes
Ventilation	H / M / L	High	High	High
Need for openings	#, proportion of height/width to size	Many entrances and exits	Many entrances and exits	Minimal entrances and exits
Acoustical Issues	dBs	Quiet space for offices and classrooms	N/A	Quiet space for offices and classrooms
Electrical issues	KWH	Lights and HVAC only	Lights and HVAC only	Lights and HVAC only
Water/sewage issues	Gal/Day	N/A	N/A	N/A
Refuse	Lbs/Day	Based on # of users	Based on # of users	Based on # of users
Health Considerations	Y / N	Strict pest and rodent control	Strict pest and rodent control	Strict pest and rodent control

Table 5.1 Function and Use Parameters

Key issues identified are the desired erection time of two weeks, the life span of two months, the possibility of reuse of the structure(s) in the same or a different location, natural ventilation and lighting, and acoustical concerns. A 12,000 square foot traditional structure cannot be erected in two weeks; a traditional structure would be ruled out in this case. A traditional structure would normally be built to have a life span of much greater than a few months; no consideration would usually be given to a traditional structure being relocated to another site and used for the same or even a different purpose. Sunlight and fresh air are critical health issues, especially in a congested environment like a public fair. A RAD structure allowing lots of sunlight and natural ventilation is highly desirable. Because office spaces and classrooms will be in close proximity to a multi-purpose and play area, a structure proposed for Option One must be divisible to prevent noise from spilling from one area to another.

Table 5.2 shows the contextual response parameters for this scenario. Again, three columns are added to the table shown in Chapter Four to consider if one large structure is used or two types of differently sized structures are used.

Contextual Response				
		Option One	Option Two - two types of RAD	
Item	Unit of Measure	1 type of RAD	Type A	Type B
Cultural Dependence	H / M / L	N/A	N/A	N/A
Climatic/Microclimatic Considerations	H / M / L	Medium	Medium	Medium
Area preparation/Site work/Foundation required	W-H	N/A	N/A	N/A
Grade of site	% slope	N/A	N/A	N/A
Limited or specific footprint	Y / N	Yes	Yes	Yes
Contamination/Hostile environment	Y / N	No	No	No
Range of internal temperature of structure	degrees F	68-75F	Indoor play area 60-90F	68-75F
Site Accessibility	H / M / L	High	High	High

Table 5.2 Contextual Response Parameters

The main issue of importance from among the contextual response parameters deals with the temperature limits of the indoor play area. This requirement does not limit the types of RAD structures that can be used. Instead, it broadens the choices for a Type A facility since the range of internal temperature is greater there than for Type B facility or if only using one structure as in Option One.

Table 5.3 displays the geometric and physical/structural parameters for the proposed educational section of the fair. The structural system and size are of particular concern for this case study.

Material Properties and Methods				
		Option One	Option Two - two types of RAD	
Item	Unit of Measure	1 type of RAD	Type A	Type B
Geometric and Physical Properties				
Structural system	self-supported or skeleton	Hard surface exterior	Hard surface exterior	Hard surface exterior
Minimum and maximum size of structure	SF / CF	N/A	N/A	N/A
Minimum and maximum size of usable space	SF / CF	12,000	6,000	Adding to 6,000
Equipment integrated into structure	Y / N	HVAC	HVAC	HVAC
Fire protection	H / M / L	High	High	High
Storm considerations	H / M / L	Texas hail storms and tornados	Texas hail storms and tornados	Texas hail storms and tornados
Seismic/Volcanic considerations	H / M / L	Low	Low	Low
Windloading	H / M / L	Medium	Medium	Medium
Snowloading	H / M / L	N/A	N/A	N/A
Mobility of structure in compact form	H / M / L	Low	Low	Low
Weight and Volume	Lbs / CF	N/A	N/A	N/A
Off the shelf or engineered for this particular use	Y / N	Either	Either	Either
Delivery time	days	N/A	N/A	N/A
Capable of withstanding long term storage	Y / N	No	No	Yes
Maintenance required during storage	W-H	N/A	N/A	No
Maintenance during deployment	W-H	Minimize	Minimize	N/A
Reconstitution effort	W-H	N/A	N/A	N/A
Part replacement	H / M / L	Low	Medium	Low

Table 5.3 Geometric and Physical Properties Parameters

The structural system must be able to withstand Texas hailstorms; due to the localized loading during a storm, the promoters may decide to have a structure(s) with a hard surfaced exterior to avoid the concern. Meeting the size requirement of 12,000 SF is not possible with all RAD structures; Option Two allows for multiple structures being added together for attainment of the overall requirement.

The next set of parameters, dealing with the erection and collapse of the structure, are listed in Table 5.4. Safety of the workers, public, and especially children is the important parameter from this table.

Material Properties and Methods				
		Option One	Option Two - two types of RAD	
Item	Unit of Measure	1 type of RAD	Type A	Type B
Erection and Collapse Considerations				
Safety of workers and public	list each item/area	Public bldg	Public bldg	Public bldg
Project Management	H / M / L	Low	Low	Low
Plans and Specifications	H / M / L	Low	Low	Low
Float	H / M / L	Low	Low	Low
Level of assembly	H / M / L	Low	Low	Medium
Collapse method	H / M / L	Low	Low	Medium
Work hours to erect/disassemble	W-H	Approx 2 crews one week	Approx 1 crew one week	Approx 1 crew one week
Skilled & non-skilled workers required	# of workers	Approx 6 per crew	Approx 6 per crew	Approx 6 per crew
Special tools & equipment required	Y / N	No	No	No

Table 5.4 Erection and Collapse Considerations Parameters

Safety concerns drive many aspects of a public building. If a RAD structure is used, the public must be protected from the mechanisms that perform the movement. Children must not be able to remove pins or tamper with connections. Any stabilizing cables or temporary anchors must be strategically placed so tripping hazards are avoided. Extra barricades may be required to prevent people from hitting their heads on low ceilings or bumping into supports.

A table listing the financial parameters is shown as Table 5.5. Since no estimates are available of the various costs, the values are left To Be Determined (TBD).

Financial				
		Option One	Option Two - two types of RAD	
Item	Unit of Measure	1 type of RAD	Type A	Type B
Material/Purchase cost	$	TBD	TBD	TBD
Deployment cost	$	TBD	TBD	TBD
Erection cost	$	TBD	TBD	TBD
Maintenance cost	$ / month	TBD	TBD	TBD
Disassembly cost	$	TBD	TBD	TBD
Reconstitution cost	$	N/A	N/A	TBD
Storage cost	$ / month	N/A	TBD	N/A

Table 5.5 Financial Parameters

5.3 SELECTION OF APPROPRIATE RAD STRUCTURES

Using the definitions provided in Chapter Two, the size, location, function, and costs of any traditional structure are important, but may become less important than mobility, transience, and speed when considering the use of a RAD structure. Figure 5.2 graphically shows some possible variations concerning these issues.

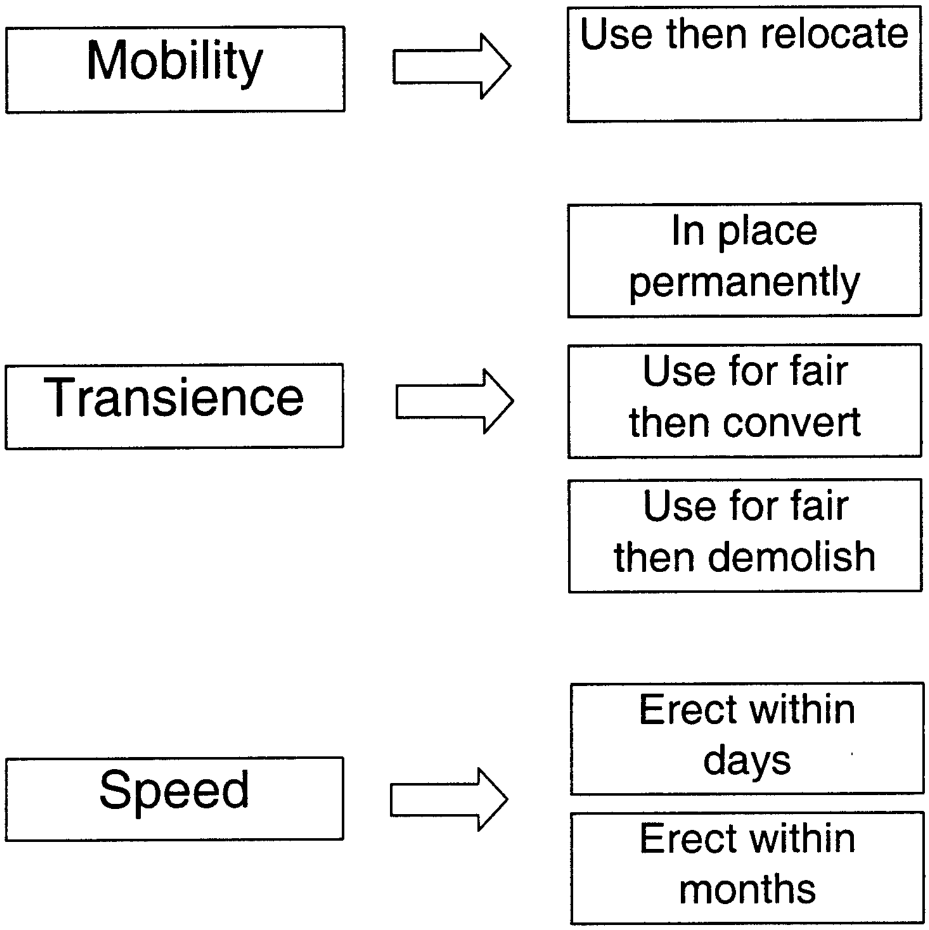

Figure 5.2 Mobility, Transience, and Speed as Considerations

If mobility is desired, a structure that can be relocated to another site should be chosen. Considering the larger structure (Type A) proposed in Option Two, a RAD structure could be built to remain in place for a few years. Similarly, Type B structures to be used as classrooms and offices could be erected, used, and then converted to another use, stored, demolished, or sold.

Certain RAD structures can be erected within days while others may take weeks or months to be designed, fabricated, and erected.

The key parameters of each table have been identified and discussed. An analytical approach can now be taken to prioritize the various parameters according to their importance and identify RAD structures that meet the requirements. The promoters may establish a committee to evaluate the tables and prioritize the data. They can then begin to choose appropriate structures meeting the crucial parameters and eliminating others that cannot satisfy the requirements. Figure 5.3 illustrates some sample results for the function and use parameters.

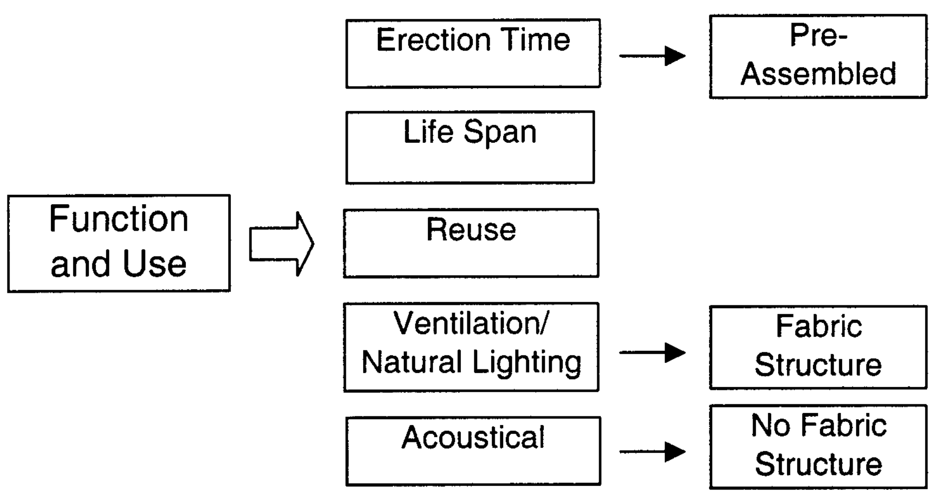

Figure 5.3 Sample of Crucial Function and Use Parameters

Five of the functions and use parameters identified earlier as particularly important are the erection time, life span, reuse, ventilation/lighting, and acoustical considerations of the structure. Two of these, erection time and ventilation/lightning, point to specific types of structures. A scissor structure could be erected in very little time by extending its members as compared to the erection of a pinned structure, which must be built from component parts. The scissor structure could also be dismantled and erected at another location, making reuse easier, which satisfies another requirement. A tensile fabric structure, as described by Bulson and having openings that allow natural light to penetrate and air to flow freely, would be an alternative to a solid walled building. However, this would not meet the requirement to separate the various activities acoustically and therefore could not be used.

Figure 5.4 shows the one contextual response parameter that is important, which is the range of internal temperature.

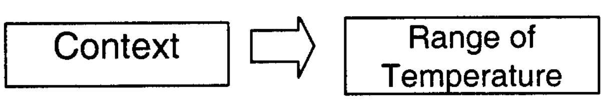

Figure 5.4 Sample of Crucial Contextual Response Parameters

Since the range of internal temperature is wider for a Type A structure than for a Type B structure or a structure under Option One, a wide range of

structures may be used. One type that would satisfy the needs is a RAD structure with a retractable roof. It offers various configurations depending upon the weather and activities.

Figure 5.5 is a representation of certain material properties and methods parameters that are important in this case study. The structural system used, the size of the structure, and safety concerns are primary concern.

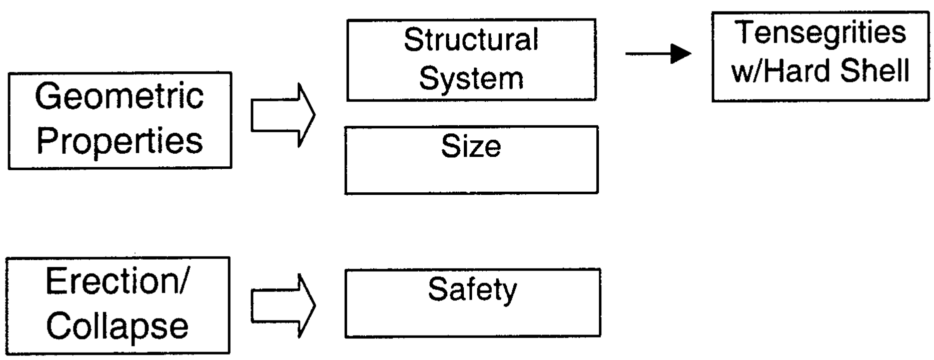

Figure 5.5 Sample of Crucial Material Properties and Methods Parameters

The possibility of hail may dictate that hard materials be used; this means that tensioned membrane structures cannot be used. Instead, skeleton or hybrid structures such as tensegrities, according to Hanaor's description from Chapter Three could be used. As a combination of rigid members and cables, tensegrities would allow for the attachment of hard covering surfaces. Scissors or other rigid member structures can also be used if they are covered with hard surfaces. The size of the facility remains a fundamental issue, and probably limits the type of

RAD structures possible under Option One. For Option Two, since more than one structure would be used to provide the required square footage, more types of structures can be considered. If speed of deployment is measured in days not months, the appropriate parameter to evaluate is delivery time. Particular concern exists for the safety of the children, but that does not necessarily limit the choice of RAD structures. It means that any mechanical connections, guy wires, and moving parts must be well marked and cordoned off.

The financial parameters are not specifically addressed in this case study. The need to keep costs low would shape the consideration of structures away from designing a new structure toward structures that are already available. The desire of the promoters to showcase new technology and display young talent would allow for the development of a new design. Controlling maintenance costs probably means using a RAD structure without mechanical parts that produce movement. Finances will impact the final decision, but they are not driving the choice of an appropriate structure.

All of the parameters presented are not applicable in every scenario, and even when they are applicable, some simply are not as important as others. Some of the important parameters point to a particular type or category of rapidly assembled or deployable structures (pre-assembled, translucent) due to the needs of the users and the facts of the scenario. Other ones simply rule out certain structures like fabric ones. This elimination can be just as effective in

determining the appropriate structure because it removes possible solutions and narrows the field of choices. A retractable roof provides expandability, but additional maintenance is required on the joints and availability of parts may be low. An inflatable structure would get attention, but relies on a compressor to maintain its integrity, and generally has a short life span, both in storage and when deployed. The strengths and weaknesses of each type of structure must be known, along with the specifics of its deployment, so that the right structure can be chosen.

While no definitive answer can be given in the case study presented, it can be summarized that an off-the-shelf design of a pre-assembled structure, as classified by JOCOTAS, would work in this situation, but would not meet the organizers' need to showcase new technology and novel ideas. Sufficient time exists to design a tensegrity structure like the tensegrity roof pictured in Section Three of Chapter Three, which describes Escrig's classification system. Similarly, a scissor structure could be designed to meet the needs of the organizers and users. A reciprocal frame building, created by O. Popovic and others, like the one shown in Figure 5.6 and falling into Hanaor's classification of a lattice structure with rigid links would be novel at the fair and attract the desired attention.

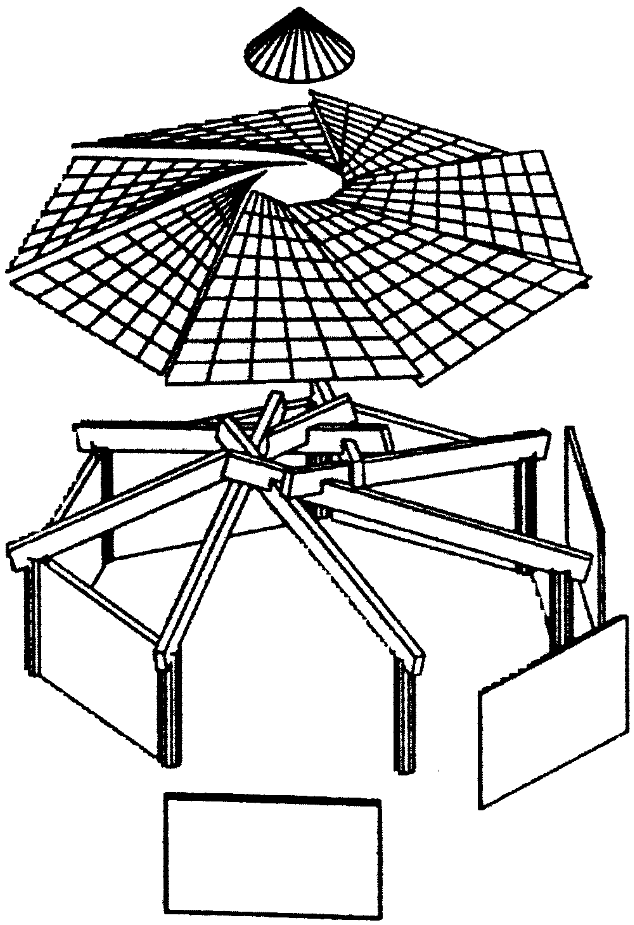

Figure 5.6 Reciprocal Frame Building by Popovic et al.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

The essence of this thesis is to develop and provide a comprehensive list and explanation of critical variables, which will help in crafting a solution based upon a thorough understanding of the situation. In order to explain fully the key requirements for a rapidly assembled or deployable structure, this study first reviews the existing classification systems of structures and then presents a comprehensive list of parameters addressing all the characteristics. This thesis provides an efficient tool for the initial investigation of factors that need to be considered in the selection of a rapidly assembled or deployable structure by framing the given scenario using thought provoking factors stimulating the engineer's education and intuition. The case study shows the decision-making and design processes for RAD structures using the new parameters. The study case illustrates that using the factors and having a clearer and more precise understanding of the scenario and the options available, a range of appropriate RAD structures for a realistic scenario can be easily chosen.

6.1 SPECIFIC CONCLUSIONS

This initial investigation of rapidly assembled or deployable structures:

1. Developed and categorized parameters necessary for the successful use of a RAD structure. Four large classifications were presented, with applicable subdivisions made.
2. Provided an overview of the existing classifications of deployable and moveable structures. Bulson, Escrig, Hanaor, and JOCOTAS divided the numerous structures into different categories, depending upon the material, shape, motion, and joints of the structure. This study has additional significance in its compilation of information from various sources and comparison of the classification systems of current researchers; this had not yet been done. To clarify the vast number of structures in this field, examples were provided of the various types of rapidly assembled or deployable structures and some possible implementations.
3. Proposed logical measurements for each parameter. Examples were provided for each different factor.
4. Demonstrated through a plausible case study the usefulness of the parameters. Using the tables provided, values were assumed for the applicable parameters. By knowing which parameters are integral or even crucial to the given situation, the array of possible structures may be efficiently evaluated for the best solution.

In addition, the decision-making and design processes for current construction projects were reviewed. Proper decision-making allows the information and conditions prerequisite for the decision to be collected, options to be created, a choice be made, and implementation occur. The design process summarizes the goals and needs of the user with the facts of the situation. An evaluation is made to determine the best option, with concurrence gained from the user.

6.2 SUGGESTIONS FOR FUTURE RESEARCH

As with any thesis, many areas worthy of exploration remain to be investigated. Follow on work could be done to rank the parameters according to their relative importance with respect to the given situation. Consideration should certainly be given to risk analysis of each type of structure with respect to various environmental and situational conditions. A computer-based application could be created to present the parameters, collect the data, and assist the user in the logic of choosing a particular structure. With this, solutions for possible scenarios may be prepared ahead of time and be available for review by interested individuals.

The study of rapidly assembled or deployable structures is gaining momentum in the international community. Follow on work will only assist other researchers in understanding the uses, strengths, and limitations of these RAD structures.

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Vita

Stephen John Donley was born on February 12th, 1968, in Greensburg, PA, to Jerome and Irene Donley. He graduated from Greensburg Central Catholic High School in 1986. In 1990, he graduated from the University of Pittsburgh with a Bachelor of Science Degree in Electrical Engineering. Also in 1990, he was commissioned an Ensign in the United States Navy Civil Engineer Corps where he has served since. He has completed tours of duty in Guam, Mississippi, and Hawaii, and is currently a Lieutenant Commander. He and his wife Barrie have three children: Emily, Sean, and Julia. He began the Master of Science program in Construction Engineering and Project Management (CEPM) at the University of Texas at Austin in September 2000.

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